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Key Points:

- We quantify topographic asymmetry caused by asymmetric glaciation
- Glacial erosion causes greater topographic asymmetry than fluvial erosion all else equal
- Glacial-interglacial cycles can cause divide migration

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:
J. Lai,
lai@gfz-potsdam.de

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Author Contributions:
Conceptualization: Jingtao Lai, Kimberly Huppert
Data curation: Jingtao Lai
Formal analysis: Jingtao Lai, Kimberly Huppert
Funding acquisition: Jingtao Lai, Kimberly Huppert
Investigation: Jingtao Lai, Kimberly Huppert
Methodology: Jingtao Lai, Kimberly Huppert
Project administration: Jingtao Lai, Kimberly Huppert
Resources: Jingtao Lai, Kimberly Huppert
Software: Jingtao Lai
Supervision: Kimberly Huppert
Validation: Jingtao Lai
Visualization: Jingtao Lai
Writing – original draft: Jingtao Lai
Writing – review & editing: Jingtao Lai, Kimberly Huppert

Climate-Driven Topographic Asymmetry Enhanced by Glaciers: Implications for Drainage Reorganization in Glacial Landscapes

Jingtao Lai[1] and Kimberly Huppert[1,2]

[1]Earth Surface Process Modelling, GFZ German Research Centre for Geosciences, Potsdam, Germany, [2]Department of Earth & Atmospheric Sciences, City College of New York, New York, NY, USA

Abstract Climate contrasts across drainage divides, such as orographic precipitation, are ubiquitous in mountain ranges, and as a result, mountain topography is often asymmetric. During glacial periods, these climate gradients can generate asymmetric glaciation, which may modify topographic asymmetry and drive divide migration during glacial-interglacial cycles. Here we quantify topographic asymmetry caused by asymmetric glaciation and its sensitivity to different climate scenarios. Using an analytical model of a steady-state glacial profile, we find that the degree of topographic asymmetry is primarily controlled by differences in the equilibrium line altitude across the divide. Our results show that glacial erosion can respond to the same climate asymmetry differently than fluvial erosion. When there are precipitation differences across the divide, glacial erosion produces greater topographic asymmetry than fluvial erosion, all else equal. These findings suggest that glaciations may promote drainage reorganization and landscape transience in intermittently glaciated mountain ranges.

Plain Language Summary In mountainous regions, the amount of rain, snow, and ice that falls and builds up often varies from one side of a mountain to the other. Over thousands to millions of years, these variations can make the length and steepness of the mountain sides differ, too. When glaciers form during ice ages, they can make this asymmetry in the topography even more pronounced. Our study looks at how glaciers affect the landscape and how glaciers and landscapes change in different climate conditions. Using a computer model, we discovered that the landscape becomes even more asymmetric when it is shaped by glaciers compared to when it is shaped by rivers. Our findings suggest that glaciers can cause landscapes to constantly change between ice ages.

1. Introduction

Drainage divides are fundamental topographic boundaries on Earth's surface that determine catchment areas for rivers and glaciers, control water and sediment budgets, and influence speciation and biodiversity (e.g., Clift & Blusztajn, 2005; Hoorn et al., 2010; Liu et al., 2024; Stokes et al., 2023). Topographic analyses, provenance, and geochronological studies suggest drainage divides are dynamic features of the landscape (e.g., Beeson et al., 2017; Bishop, 1995; Gilbert, 1877; Hu et al., 2021; Willett et al., 2014). While an increasing number of studies have focused on divide mobility in landscapes dominated by rivers (e.g., Dahlquist et al., 2018; He et al., 2021; Hu et al., 2021; Schildgen et al., 2022; Shi et al., 2021; Whipple et al., 2017), the stability of drainage divides in glacial landscapes has received less scrutiny, even though past glaciations have modified up to 30% of Earth's surface topography (Herman et al., 2021).

In glaciated mountain ranges, asymmetric glaciation across the ridgeline can result in cross-divide contrasts in erosion rates, driving the divide to migrate toward the side with slower erosion rates (Dortch et al., 2011; Gilbert, 1904; Lai & Huppert, 2023; Oskin & Burbank, 2005). As a result, these mountain ranges tend to develop asymmetric topography with a horizontal offset between the main drainage divide and the center of the mountain range. For example, glaciated mountain ranges in the Northern Hemisphere usually have longer north-facing valleys than south-facing ones (Figure 1a and Figure S1 in Supporting Information S1), because north-south contrasts in solar insolation result in larger glaciers on north-facing slopes (Dortch et al., 2011; Evans & Cox, 2005; Lai & Huppert, 2023).

Asymmetric glaciation can occur when ice preferentially accumulates on one side of the drainage divide due to topographic shading, orographic rainfall, and/or wind-blown redistribution of snow (Dahl & Nesje, 1992;

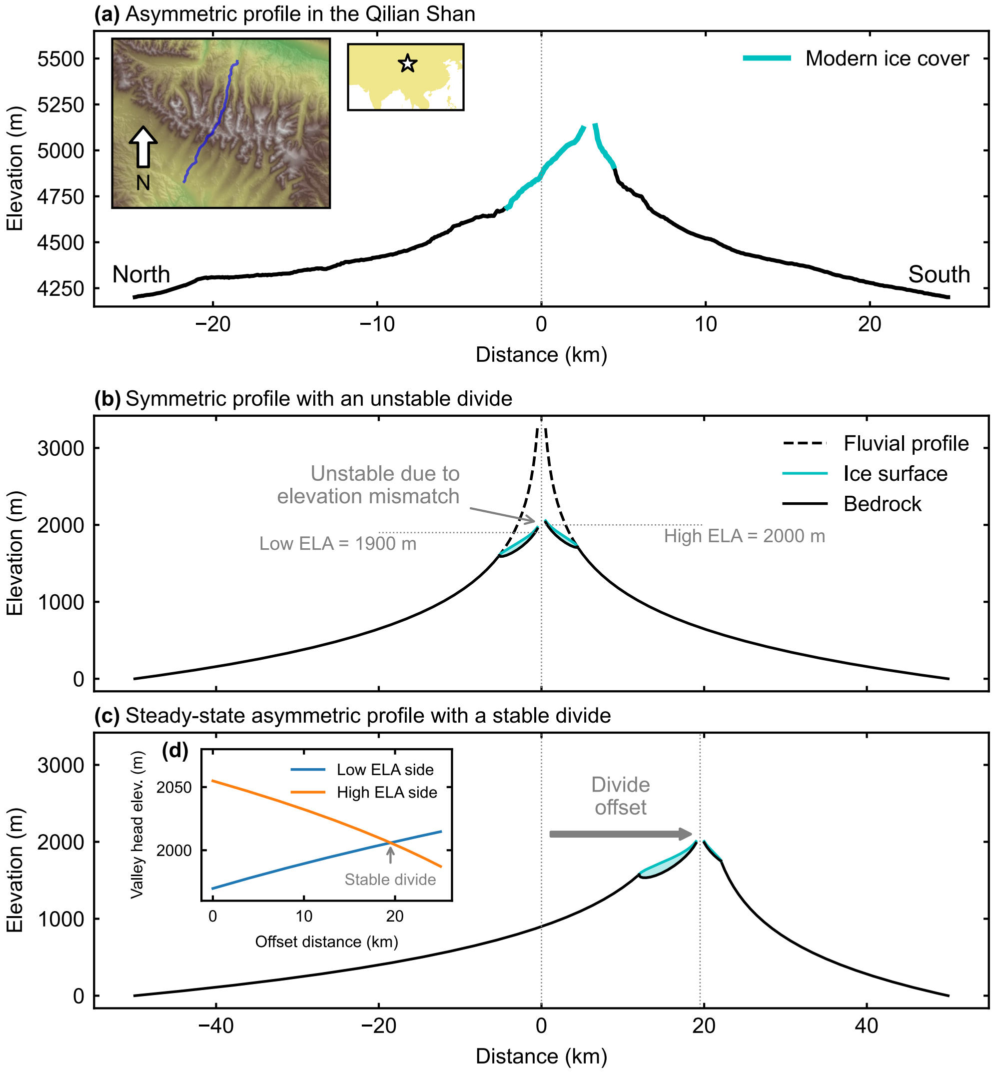

Figure 1. Topographic asymmetry created by asymmetric glaciation. (a) An example of an asymmetric valley profile from the Qilian Shan. Light blue parts indicate modern ice surface. The northern slope (left) has more extensive ice cover than the southern slope (right). Insets show the location of the valley profile and the mountain range. (b) Analytical solution of a valley profile assuming the two sides have the same length. The drainage divide is unstable due to elevation mismatch at the valley heads. (c) Analytical solution of a steady-state asymmetric valley profile with an offset between the divide and mountain center. The low-ELA side must be longer than the high-ELA side to maintain a stable divide. We note that the model may over predict deepening below the glacial portion of the profile, but this does not affect the valley head elevations (Deal & Prasicek, 2021) nor divide offset distances. (d) The change of valley head elevation as a function of divide offset distance. This relationship is nonlinear due to the concavity of the steady-state profiles.

Evans, 1977; Foster et al., 2010; Margason et al., 2023; Olson & Rupper, 2019). Different climate gradients lead to various degrees of glacial asymmetry. For example, differences in equilibrium line altitudes (ELAs) between contemporary pole-facing and equator-facing glaciers are 70–320 m, with greater differences in regions with drier climates and steeper slopes (Evans & Cox, 2005). However, the impact of different degrees of glacial asymmetry on the offset of drainage divides from the range centerline has not been well quantified. Moreover, some climate conditions, such as orographic rainfall, can also cause topographic asymmetry in fluvial systems (e.g., Roe et al., 2003; Schildgen et al., 2022), but the extent to which drainage divides may be offset by glacial erosion compared to fluvial incision under the same cross-divide climate contrasts has not been compared.

A better quantification of the extents of topographic asymmetry created by asymmetric glaciation is important for understanding the stability of drainage divides during Quaternary glaciations. In many intermittently glaciated mid-latitude mountain ranges, the dominant erosion processes constantly shift between glacial erosion and fluvial incision during glacial-interglacial cycles (e.g., Norton et al., 2010). If glacial erosion can create a different degree of topographic asymmetry than fluvial erosion under the same cross-divide climate contrasts, the drainage divide may tend toward different stable positions during glacial-interglacial cycles, promoting continuous drainage reorganization in intermittently glaciated mountain ranges.

In this work, we use steady-state topography as a reference state to understand the direction toward which landscapes evolve during glacial-interglacial cycles (Whipple & Tucker, 1999; Willett & Brandon, 2002). We quantify topographic asymmetry wrought by asymmetric glaciation by solving for the stable divide location in glacial profiles developed under cross-divide climate contrasts. We explore the sensitivity of divide location to various climate scenarios and compare the extent of glacially-driven topographic asymmetry to fluvially-driven topographic asymmetry. Our results indicate that glacial erosion creates higher degrees of topographic asymmetry than fluvial erosion at steady state, suggesting that intermittent glaciations may promote drainage reorganization.

2. Methods

We build an analytical one-dimensional profile model of two head-to-head fluvial valleys glaciated in their headwaters in steady state (see details in Supporting Information S1). The two glaciated valleys have different glacier ELAs across the drainage divide. In this model, we prescribe drainage area using an empirical scaling with downstream or down-glacier length (Hack, 1957; Prasicek et al., 2020).

In the fluvial portion of the valley profile, we calculate the erosion rate E [L T^{-1}] using the stream power river incision model (Ferrier et al., 2013; Howard & Kerby, 1983; Whipple & Tucker, 1999):

$$E = K_f (PA)^m S^n \tag{1}$$

where P [L T^{-1}] is the mean annual precipitation, A [L^2] is upstream drainage area, S [ ] is local gradient, K_f [L^{1-3m} T^{m-1}] is the fluvial erodibility coefficient, and m [ ] and n [ ] are constants. Assuming the erosion rates everywhere balance the rock uplift rate, this equation leads to an analytical solution for steady-state fluvial profiles (Whipple & Tucker, 1999).

We model glacial erosion rate as a function of the sliding velocity of the glacier u_s [L T^{-1}] (Cook et al., 2020; Herman et al., 2015; Humphrey & Raymond, 1994; Koppes et al., 2015):

$$E = K_g u_s^{\ell} \tag{2}$$

where K_g [L$^{1-\ell}$ T$^{\ell-1}$] is an erodibility coefficient and ℓ [ ] is a constant that ranges from 0.65 to 2 (Cook et al., 2020; Herman et al., 2015; Koppes et al., 2015). To apply this erosion law, we use the sliding ice incision model (Deal & Prasicek, 2021), which derived analytical solutions for bedrock elevation and ice surface elevation at steady state based on the Shallow Ice Approximation (Hutter, 1983) and an elevation-dependent surface mass balance model.

In our head-to-head valley profile model, we use the difference in valley head elevation across the divide, that is, the elevation at a fixed hillslope length from the divide, as the criterion for divide stability (Forte & Whipple, 2018). If the valley head is covered by glacial ice, we use the ice surface elevation as the valley head elevation rather than the bedrock elevation. The divide is unstable when the two sides have different elevations at their valley heads because the side with a lower channel head will have a steeper hillslope gradient below the ridgeline (Figure 1b). It will consequently erode faster than the other side, driving the ridgeline toward the higher valley head side (Forte & Whipple, 2018). We solve for the stable divide location by changing the divide location iteratively until the valley head elevations are the same across the divide (Figure 1c).

3. Results

3.1. Cross-Divide ELA Difference Controls Divide Location Offset

Asymmetric glaciation can result in elevation mismatch at the valley heads if the divide remains at the centerline of the range (Figure 1b). The side with a lower ELA will have a lower valley head than the high-ELA side. This

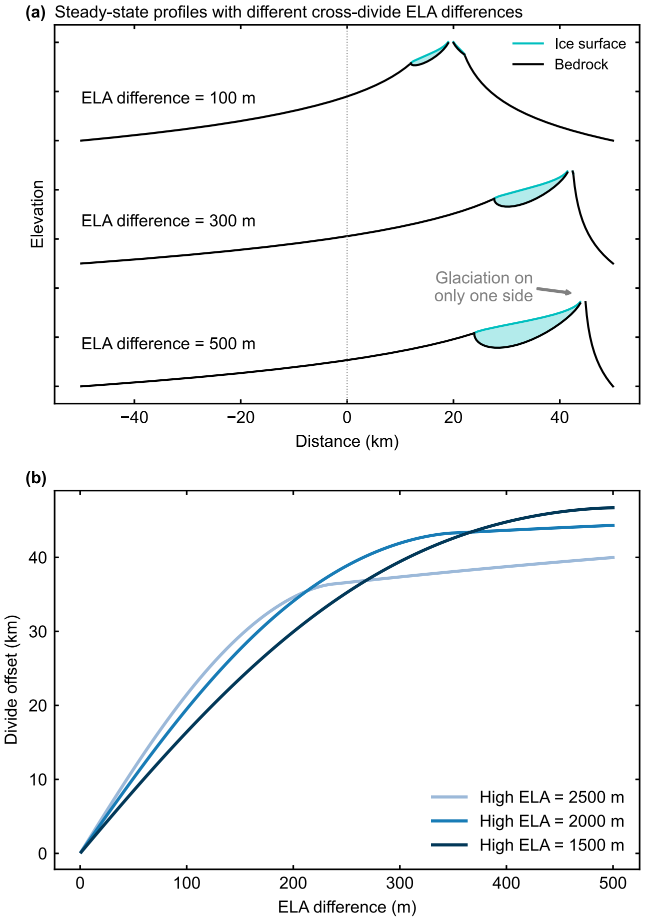

Figure 2. (a) Three cases with different cross-divide equilibrium line altitude (ELA) differences and different degrees of topographic asymmetry. The high ELA is 2,000 m in all three cases. (b) Divide offset distance as a function of cross-divide ELA differences for glaciated profiles with different ELAs on the high-ELA (right-hand) side.

elevation mismatch will create a cross-divide difference in erosion rates and cause divide migration (Forte & Whipple, 2018). Therefore, the steady state divide location must shift to the high-ELA side so that the low-ELA side is longer than the high-ELA side and the two sides have equal valley head elevations (Figures 1c and 1d).

When asymmetric glaciation generates topographic asymmetry, this instigates a positive feedback, since topographic asymmetry in turn enhances the asymmetry in glacier size. In an asymmetric mountain range, the low-ELA side has higher valley head elevation than in the symmetric case, and the area above the ELA increases (compare Figures 1b and 1c). As a result, the glacier on the low-ELA side accumulates more ice than in the symmetric case. Conversely, the high-ELA side has a smaller ice accumulation area and consequently a smaller glacier size than in the symmetric case (Figures 1b and 1c).

We explore the extents of divide location offset from the range center under various scenarios of asymmetric glaciation by varying the ELAs and cross-divide ELA differences across the divide. Our results indicate that cross-divide ELA differences are the primary control on divide location offset; greater ELA differences lead to greater extents of topographic asymmetry (Figure 2 and Figure S2 in Supporting Information S1). In a 100-km wide mountain range, the divide can be offset up to 40 km from the range center when the ELA difference across the divide is 300 m (Figure 2 and Figure S2 in Supporting Information S1). The absolute values of the ELAs on each side of the divide have a minor impact on divide offset. Cross-divide ELAs at different elevations but the same difference apart generate similar topographic asymmetry (Figure 2b).

When the ELA conditions only allow for glaciation on one side of the mountain range (e.g., the lower two profiles in Figure 2a), the divide offset is less sensitive to cross-divide ELA differences than in cases where glaciation occurs on both sides of the divide (decrease of slope in the two light blue curves in Figure 2b as large ELA differences result in glaciation on only one side of the divide). This is because fluvial erosion is less efficient than glacial erosion and generates greater relief under the same climatic and tectonic forcing. Therefore, the fluvial valley head elevation is more sensitive to changes in valley length (Figure S3 in Supporting Information S1), and less divide offset is required to ensure adjacent fluvial valley heads are at equal elevation with glacial channel heads.

We further investigate these relationships using different erosion law exponents (n in Equation 1 and ℓ in Equation 2), and our results show that these exponents have limited impact on the extents of divide offset under different ELA scenarios (Figure S4 in Supporting Information S1). We also vary the uplift and precipitation rates and explore their effect on these relationships. Our results show that in all cases, the divide location offset increases with greater cross-divide ELA differences (Figure S5 in Supporting Information S1).

3.2. Glaciation Enhances Precipitation-Driven Asymmetry

Asymmetric glaciation can alternately or additionally result from precipitation asymmetry across the divide. In such cases, the purely fluvial topography is also asymmetric, with the wetter side being longer. To compare the divide offset caused by glacial and fluvial processes, we impose a spatial change in precipitation rate across the divide and adjust the ELAs according to the change in precipitation rate:

$$\Delta \text{ELA} = -\frac{\Delta P}{\delta} \tag{3}$$

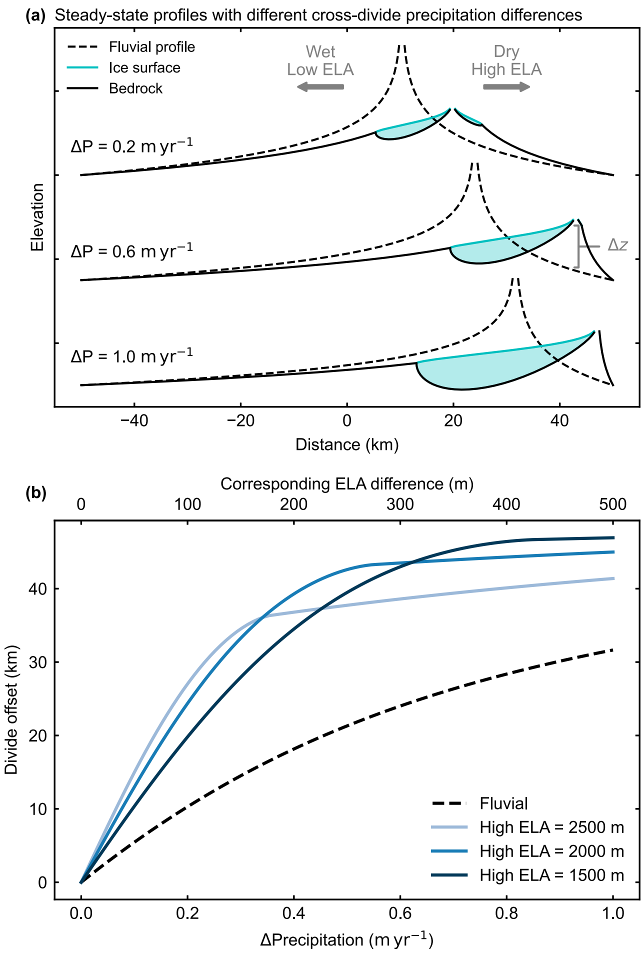

Figure 3. (a) Three cases with different cross-divide precipitation differences and different degrees of topographic asymmetry. The precipitation rate on the left-hand side is higher than the right-hand side, and consequently the left-hand side has lower equilibrium line altitude (ELA). The precipitation rate and ELA on the right-hand side is 1 m yr^{-1} and 2,000 m respectively in all three cases. Solid lines are glaciated profiles, and dashed lines are purely fluvial profiles. Δz is the elevation difference used to calculate divide migration timescale. In all three cases, glacial topography has greater asymmetry than fluvial topography. (b) Divide offset distance from the center of the mountain range as a function of cross-divide precipitation differences. Solid lines are divide offset distances for glaciated profiles with different ELAs on the high-ELA (right-hand) side. The dashed line shows divide offset distances for non-glaciated, purely fluvial profiles.

where δ [T^{-1}] is the solid precipitation lapse rate (Deal & Prasicek, 2021). The negative sign indicates that an increase in precipitation lowers the ELA whereas a decrease raises it. Although this imposed step change in precipitation across the divide neglects spatial variations in orographic precipitation (e.g., Roe et al., 2003), it captures first-order cross-divide precipitation asymmetry that can be easily compared to observed orographic rainfall gradients.

Our results reveal that, in comparison with fluvial topography, glacial topography exhibits greater topographic asymmetry given the same precipitation difference across the divide (Figure 3), regardless of the cross-divide differences in precipitation rates or the ELAs on each side of the divide (Figure 3b). For a 100-km wide mountain range, glacial erosion is capable of shifting the divide as much as 20 km toward the side with lower precipitation, compared to steady-state fluvial profiles developed under the same precipitation gradient (differences between solid lines and the dashed line in Figure 3b).

3.3. Timescales of Drainage Divide Migration

Our finding that glacial erosion causes greater topographic asymmetry than fluvial erosion under the same climate gradients suggests that drainage divides may migrate over the course of glacial-interglacial cycles. The timescales over which this divide migration occurs affect how mobile a divide is - in other words, the rate of divide migration between fluvial and glacial steady states determines whether divides are continuously moving during glacial-interglacial cycles. We use the uplift rate U and the difference in elevation Δz between the steady-state glacial and fluvial profiles (e.g., solid lines vs. dashed lines in Figure 3a) at the glacially-controlled divide location to estimate the time τ required for topography to reach a stable configuration when transitioning between fluvially- and glacially-controlled asymmetry:

$$\tau = \frac{\Delta z}{U} \tag{4}$$

This calculation provides a minimum estimate of the time required to reach divide stability because it neglects erosion, which, if taken into account ($\tau = \Delta z/(U - E)$), would work against uplift to increase the time required for the elevation to increase at the glacially-controlled divide location.

Our results show that the estimated minimum times required to reach steady state are over 100 kyr for most climate conditions (Figure 4). Moderate cross-divide precipitation differences result in the longest durations to reach divide stability (Figure 4) because both small and large cross-divide precipitation differences lead to short divide migration distances (differences between solid and dashed lines in Figure 3b). Lower ELAs result in shorter durations to reach divide stability than higher ELAs (Figure 4) because glacial erosion prevents the divide from rising too high above the ELA, and low ELAs lead to small elevation increases at the drainage divide.

4. Discussion

Our estimates of divide location offset assume that, under constant conditions, topography reaches a steady-state condition with erosion rates everywhere equal to uplift rates. Although most glacial landscapes may not be in steady state due to the relatively recent onset of Quaternary glaciations compared to typical landscape response times (Herman et al., 2018), steady-state topography is still a useful reference condition to understand the trajectory of landscape evolution and the response of surface topography to changes in tectonic and climatic

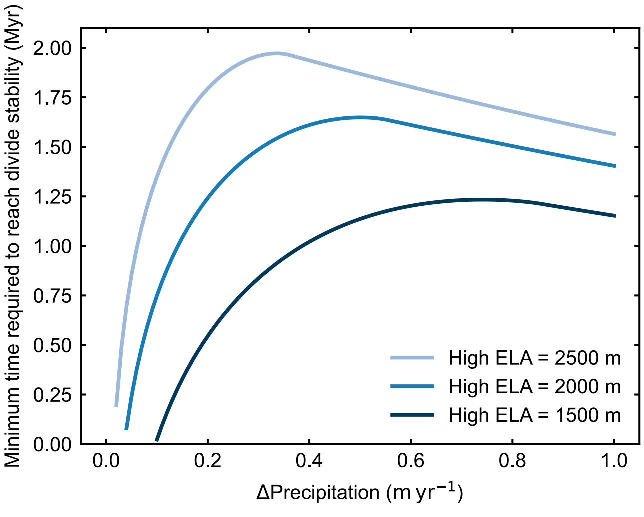

Figure 4. Estimated minimum time required to reach steady state as a function of cross-divide precipitation differences.

conditions (e.g., Prasicek et al., 2020; Whipple & Tucker, 1999; Willett & Brandon, 2002). Previous studies indicate that glacial topography can be created rapidly during early glaciations and persist through subsequent glaciations (Leith et al., 2014; Shuster et al., 2005). Also, the correlation between mountain heights and paleo glacier ELAs globally indicates that glacial topography can be preserved through repeated glacial cycles (Egholm et al., 2009). These observations suggest that some glaciated landscapes may approach a quasi-steady state after multiple glacial cycles.

Using a range of cross-divide ELA differences similar to observed values (Evans & Cox, 2005), the divide offsets we predict in our models are similar to divide offsets observed in asymmetrically glaciated mountain ranges worldwide, including the Qilian Shan, the Ladakh Range, and the Teton Range (Figure 1a and Figure S1 in Supporting Information S1). Asymmetric glaciation has been suggested to cause divide migration in each of these ranges (Dortch et al., 2011; Foster et al., 2010; Lai & Huppert, 2023). In the Qilian Shan, the observed divide offset distance is ~5 km across the 50-km wide range (Figure 1a). Similarly, in the Teton Range, the divide is offset 5–10 km across the 20-km wide mountain range (Figure S1b in Supporting Information S1; Foster et al., 2010). These distances are consistent with the 10%–40% divide offsets we predict in our modeling under typical cross divide climate contrasts, suggesting that climate gradients and asymmetric glaciation may indeed be the primary drivers of topographic asymmetry in these mountain ranges.

Our results show that glacial topography has greater topographic asymmetry than fluvial topography under the same climate gradient (Figure 3). Because steady state is a reference condition toward which landscapes evolve (Willett & Brandon, 2002), mountain ranges may tend toward more asymmetric configurations when they are glaciated, potentially causing divide migration during glacial-interglacial cycles. Our results also show that divide offset distance is mostly controlled by cross-divide ELA differences, and it is less sensitive to the absolute values of ELA (Figure 2b). This finding suggests that glacially-driven divide migration can occur even in mountain ranges that are only sparsely glaciated near the drainage divide. Therefore, our results suggest a widespread occurrence of glacially-driven divide migration given the ubiquity of precipitation gradients and solar insolation contrasts that can drive ELA differences across drainage divides.

More importantly, our estimates show that the durations of divide migration are at least several hundred thousand years, and more commonly >1 Myr, for typical climate conditions (Figure 4). These timescales of divide migration are much longer than typical 40–100 kyr glacial-interglacial cycles, and intermittently glaciated landscapes are thus unlikely to reach steady-state configurations during a single glacial period (Lai & Huppert, 2023). Because fluvial topography tends toward a less asymmetric configuration than glacial topography under a given climate gradient, the divide may migrate toward different stable positions during glacial and interglacial periods, prolonging the development of steady state topography. Therefore, periodic climate disturbances in the Quaternary may have caused persistent drainage reorganization in mountain ranges alternately shaped by glacial and fluvial erosion.

5. Conclusions

Using an analytical model of a steady-state fluvial-glacial profile, we quantified topographic asymmetry caused by asymmetric glaciation. Our results show that, under analogous cross-divide precipitation differences, glacial erosion creates greater topographic asymmetry than fluvial erosion at steady state. The timescales required for drainage divides to migrate between fluvially and glacially controlled positions under typical climate gradients are at least several hundred thousand years - much longer than Quaternary glacial-interglacial periods. This implies that intermittent glaciations can induce persistent divide migration and drainage reorganization in mountain ranges.

Data Availability Statement

The Sliding Ice Incision Model is available in a Zenodo repository (Deal, 2020). The Python scripts used to calculate results presented in this work is also archived in a Zenodo repository (Lai, 2024).

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