Climate-driven topographic asymmetry enhanced by glaciers: Implication 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, 14473 Potsdam, Germany

[2]Department of Earth & Atmospheric Sciences, City College of New York, NY 10031, USA

Key Points:

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

Corresponding author: Jingtao Lai, `lai@gfz-potsdam.de`

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 (ELA) 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 looked 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 play a significant role in changing the landscape over time, especially in places where the climate cycles periodically glaciate the landscape.

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). Topographic analyses, provenance, and geochronological studies suggest drainage divides are dynamic features of the landscape (e.g., Willett et al., 2014; Hu et al., 2021). 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 towards 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. 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; 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., 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 extent 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. If glacial topography has a different degree of topographic asymmetry than fluvial topography under the same cross-divide climate contrasts, the drainage divide may constantly migrate between a glacially-controlled stable divide location and a fluvially-controlled one.

In this work, we quantify topographic asymmetry wrought by asymmetric glaciation by solving for the stable divide location of steady-state 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 divide mobility.

2 Methods

In this work, we use the steady-state position of drainage divides to understand the impact of asymmetric glaciation on the degree of topographic asymmetry. We build a one-dimensional profile model of two head-to-head glaciated valleys with different glacier ELAs across the drainage divide. In the 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 (Howard & Kerby, 1983; Ferrier et al., 2013; Whipple & Tucker, 1999):

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

where P [L] is the mean annual precipitation, A [L^2] is upstream drainage area, S [ ] is local gradient, K_f [L^{1-3m} T^{-1}] is the fluvial erodibility coefficient, and m [ ] and n [ ] are constants. Assuming the erosion rate everywhere balances the uplift rate and approximating the drainage area by using the Hack's law, this equation leads to an analytical solution for the steady-state fluvial profile (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). The sliding velocity is commonly determined using the Shallow Ice Approximation (SIA; Hutter, 1983) in previous models of glacial landscape evolution (e.g., Braun et al., 1999). We use the sliding ice incision model (Deal & Prasicek, 2021), which introduced several simplifications to the SIA and derived analytical solutions for bedrock elevation and ice surface elevation at steady state.

In our head-to-head valley profile model, we use the difference in valley head elevation across the divide, i.e., 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 stable when the two sides have the same elevation at the valley head. If the valley head elevations are not equal, we change the divide location until the elevations the same (Fig. 1).

3 Results

3.1 ELA contrast 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 (Fig. 1a). The side with a lower ELA has lower valley head than the high ELA side. In order to compensate for this elevation mismatch, the drainage divide needs to shift towards the side with the higher ELA, so that the low-ELA side is longer and consequently higher at the valley head than in the pre-migration configuration (Fig. 1b and c). Similarly, the high ELA valley head lowers if the divide migrates towards the high ELA side.

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, allowing the glacier to accumulate more ice. Conversely, the high-ELA side has a smaller ice accumulation area and consequently, a smaller glacier size than in the symmetric case (Fig. 1b).

We explore the extents of divide location offset from the range center under various scenarios of asymmetric glaciation by varying the ELAs and differences in ELAs across the divide. Our results indicate that differences in ELAs are the primary control on divide location offset; greater ELA contrasts lead to greater extents of topographic asymmetry (Figs. 2 and 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 (Figs. 2 and S1). The absolute values of the ELAs on each side of the divide have a minor im-

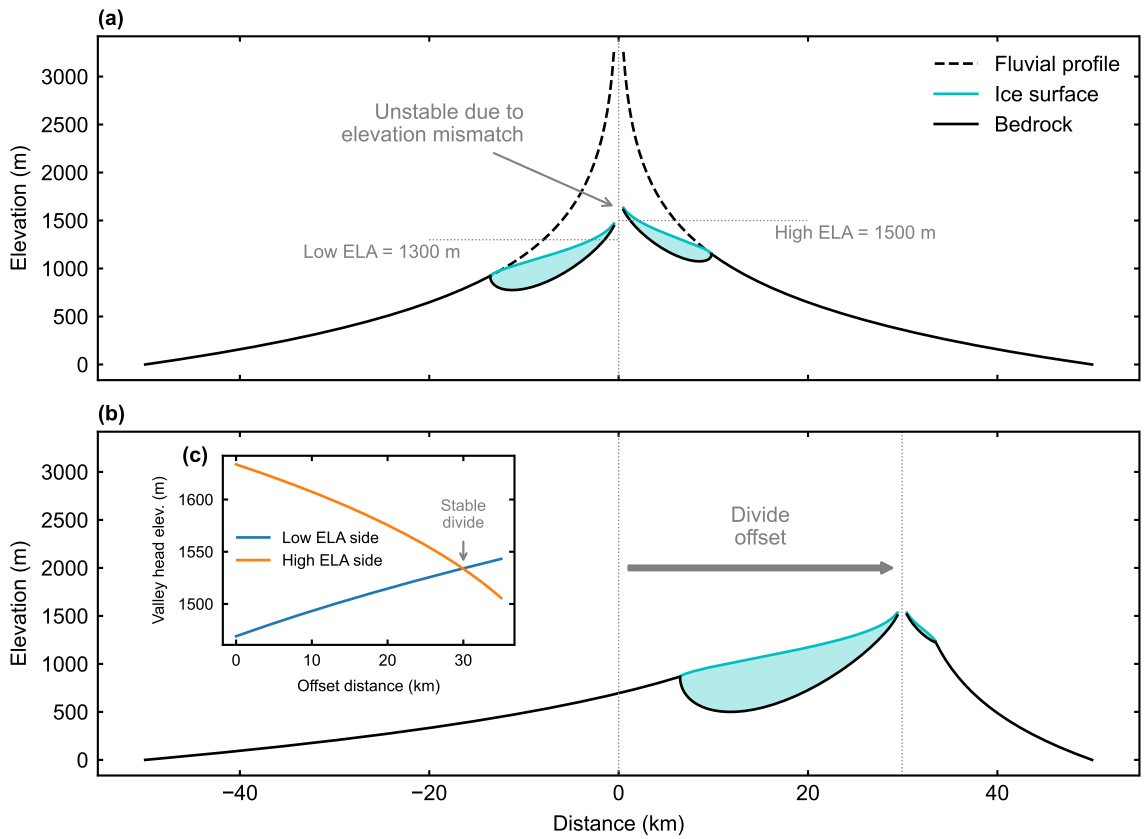


Figure 1. Topographic asymmetry created by an ELA contrast. (a) The drainage divide is unstable due to elevation mismatch if the two sides have the same length. (b) The low ELA side must be longer than the high ELA side to maintain a stable divide. (c) The change of valley head elevation as a function of divide offset distance. This relationship is nonlinear due to the concavity of the steady-state profiles.

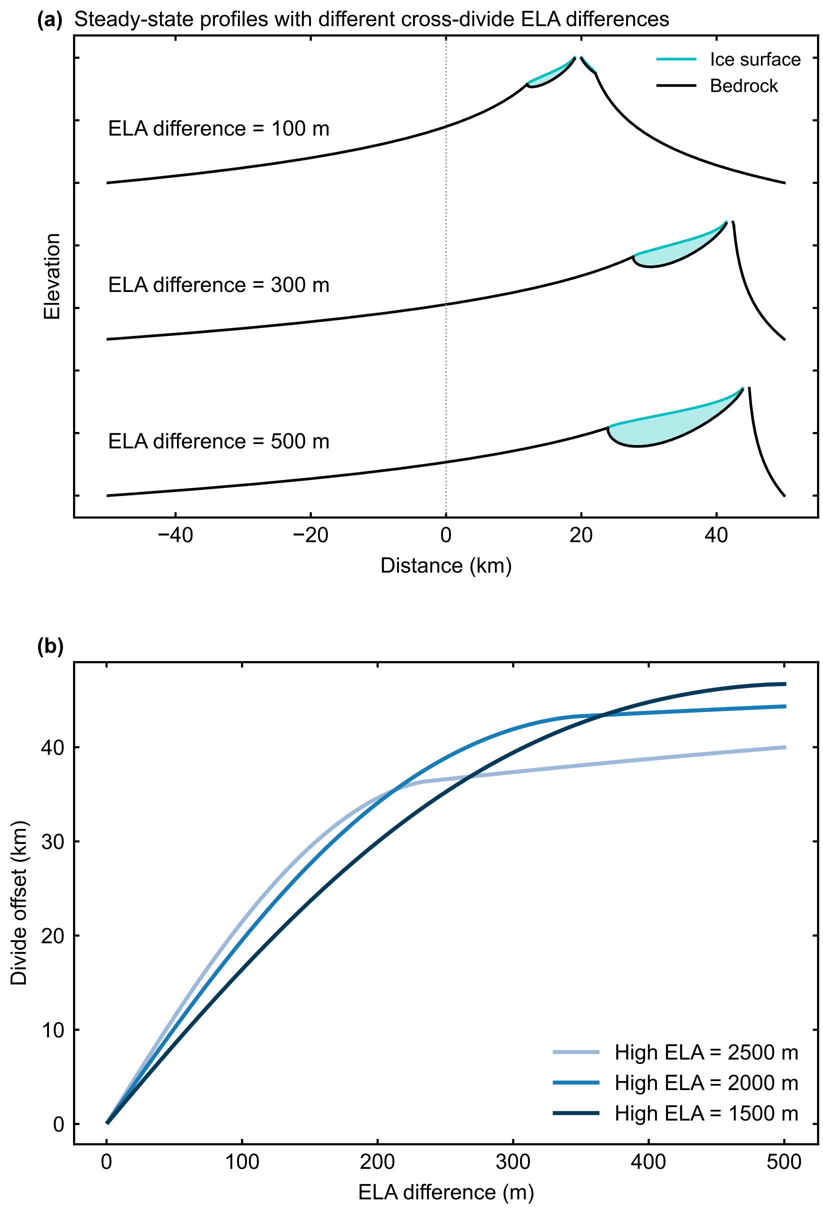


Figure 2. Three cases with different ELA contrasts and different degrees of topographic asymmetry. The high ELA is 2000 m in all three cases. (b) Divide offset distance as a function of ELA differences.

pact on divide offset. Cross-divide ELAs at different elevations but the same difference apart generate similar topographic asymmetry (Fig. 2b).

When the ELA conditions only allow for glaciation on one side of the mountain range (e.g., the lower two profiles in Fig. 2a), the divide offset is less sensitive to ELA differences than in cases where glaciation occurs on both sides of the divide (decrease of slope in Fig. 2b as large ELA differences result in glaciation on only one side of the divide). This is a result of the different efficiencies of fluvial and glacial erosion in limiting relief. Because fluvial relief is greater than glacial relief under the same climatic and tectonic forcing, the fluvial valley head elevation is more sensitive to changes in valley length (Fig. S2). Therefore, less divide offset is required to ensure adjacent fluvial valley heads are at equal elevation.

We further investigate these relationships using different erosion law exponents (n in Eq. 1 and ℓ in Eq. 2), and our results show that these exponents have limited impact on the extents of divide offset under different ELA scenarios (Fig. S3).

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:

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

where δ [ ] 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.

Our results reveal that, in comparison with fluvial topography, glacial topography exhibits a greater degree of topographic asymmetry given the same precipitation contrast across the divide (Fig. 3), regardless of the cross-divide contrasts in precipitation rates or the ELAs on each side of the divide (Fig. 3b). For a 100-km wide mountain range, glacial erosion is capable of shifting the divide as much as 20 km towards 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 Fig. 3b).

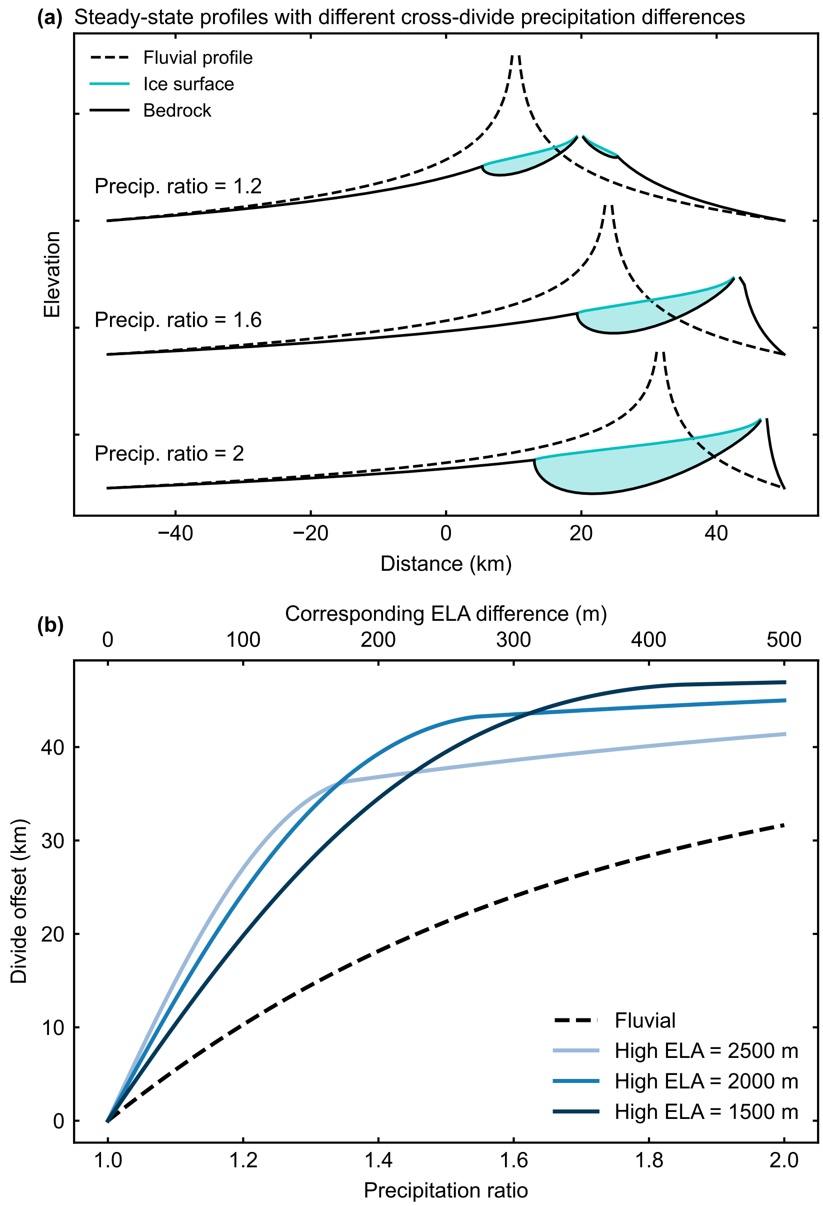


Figure 3. (a) Three cases with different precipitation contrasts and different degrees of topographic asymmetry. The high ELA is 2000 m in all three cases. (b) Divide offset distance as a function of precipitation differences.

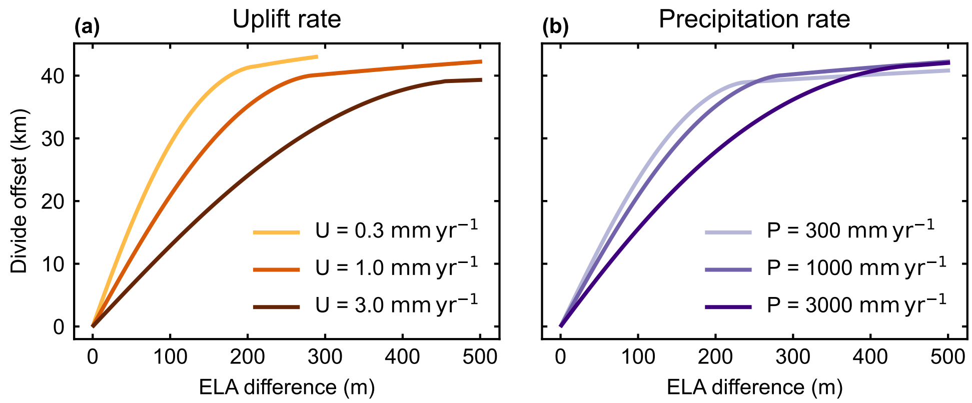


Figure 4. Divide offset distance as a function of ELA differences in cases with (a) different uplift rates and (b) precipitation rates

3.3 Sensitivity to uplift and precipitation

We vary the uplift and precipitation rates and explore their impact on topographic asymmetry. Our results show that in all cases, the divide location offset increases with greater cross-divide ELA differences (Fig. 4). Higher uplift rates generally result in shorter divide offset distance for the same ELA difference (Fig. 4a).

Precipitation rates also modify the relationships between cross-divide ELA differences and divide offset distances. We consider scenarios with different uniform precipitation rates on both sides of the divide. When the cross-divide ELA difference is small, higher precipitation rates require shorter divide offset distances for valley head equilibrium. On the other hand, when the ELA difference is large, higher precipitation rates require further divide offset (Fig. 4b).

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. This steady state may not exist for glacial topography due to the relatively recent onset of Quaternary glaciations and the short timescales of glacial cycles compared to typical landscape response times (Herman et al., 2018). However, it has been suggested that glacial topography is created rapidly during early glaciation events and persists through the following glaciations (Leith et al., 2014; Shuster et al., 2005). The correlation between mountain heights and paleo glacier ELAs globally also suggest that glacial topography can be maintained through repeated glacial cycles (Egholm et al., 2009). These observations support the notion that glaciated landscapes adjust their topography so erosion rates approximately balance uplift rates through multiple glacial cycles, making the glacial steady-state we consider a useful reference condition to understand the direction of landscape evolution and the response of surface topography to changes in tectonic and climatic conditions (e.g., Whipple & Tucker, 1999; Prasicek et al., 2020).

The divide offsets we predict in our models are of similar scale to divide offsets observed in asymmetrically glaciated mountain ranges. For instance, in the Teton Range in Wyoming, USA, the divide has migrated 5-10 km in a 20-km wide mountain range (Foster et al., 2010). This distance is consistent with the 20-40% divide offsets we predict in our modelling, suggesting that the drainage divide in the Teton Range may be close to a stable location.

Our results show that glacial topography has higher degrees of topographic asymmetry than fluvial topography under the same precipitation gradient. Because steady state is a reference condition towards which landscapes evolve (Willett & Brandon, 2002), glaciated mountain ranges may tend towards higher degrees of topographic asymmetry during glacial periods, compared to the more symmetric stable fluvial configurations they may tend towards during interglacial periods. Consequently, drainage divides may oscillate between their glacially- and fluvially-controlled stable locations during glacial-interglacial cycles in mountain ranges that are intermittently glaciated.

Similarly, when ELA contrasts are driven by differences in solar insolation, repeated glaciation may also cause divide migration because solar insolation contrasts create different topographic asymmetry in glacial and fluvial landscapes. Our results show that, the low ELA side, i.e., the low insolation side, has longer valleys than the high ELA side. On the contrary, contrasts in solar insolation create shorter valleys on the low insolation side in fluvial topography, because low solar insolation promotes dense vegetation cover and protects the bedrock from erosion (Richardson et al., 2020; Smith & Bookhagen, 2021).

Our results suggest that intermittent glaciations may promote drainage reorganization and landscape transience given the ubiquity of precipitation gradients and solar insolation contrasts across drainage divides. To understand the timescales over which drainage reorganization may occur, we consider an unstable glacial valley profile with

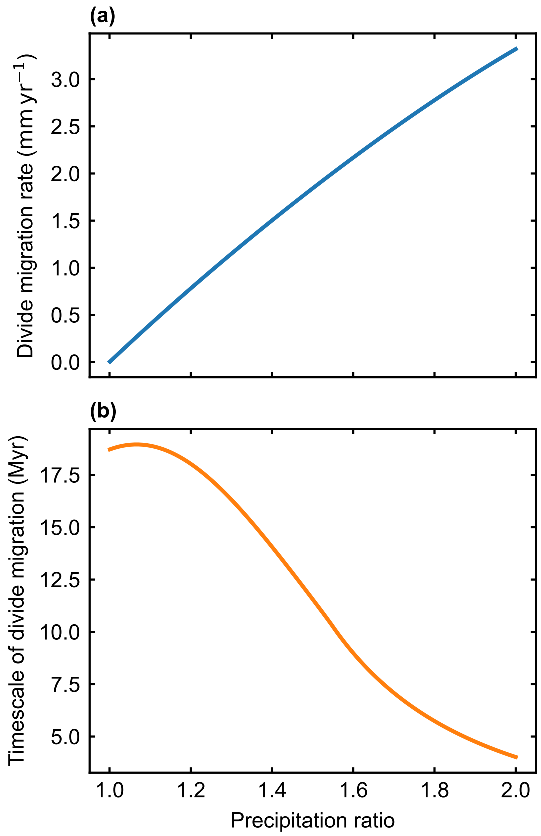


Figure 5. Estimated rates (a) and timescales (b) of divide migration as a function of precipitation differences

a fluvially-controlled divide location. We increase the uplift rate on the low ELA side until its valley head elevation matches the elevation on the high ELA side. We then use the difference between the uplift rates on the two sides to approximate the cross-divide contrast in erosion rates, and we can calculate a horizontal divide migration rate [L T^{-1}] (Beeson et al., 2017; Hu et al., 2021; Schildgen et al., 2022):

$$V_d = \frac{\Delta E}{S_1 + S_2} \tag{4}$$

where ΔE [L T^{-1}] is the difference in erosion rates, and S_1 and S_2 are slopes near valley heads on the two sides. The divide migration timescale [T] can then be estimated as

$$\tau = \frac{x_d}{V_d} \tag{5}$$

where x_d [L] is the divide migration distance.

We estimate the rates and timescales of divide migration for cases where asymmetric glaciation is created by precipitation gradients. These approximations of divide migration rates are several millimeters per year, and the timescales of divide migration range from 5 to 18 million years (Fig. 5). The rates of divide migration increase with greater cross-divide precipitation differences because greater precipitation differences create greater differences in valley head elevations and consequently faster erosion rates near the divide (Fig. 5a). The faster divide migration rates result in shorter timescale of divide migration in cases with greater precipitation differences, although they also require farther divide migration distance (Fig. 5b).

These rate and timescale estimates do not account for the transient evolution of topography as it adjusts between steady states. As the divide migrates toward a glacially-controlled stable location, we anticipate a decline in the transient migration rate because the cross-divide difference in erosion rate approaches zero as the divide moves toward a stable location. Therefore, our estimates of divide migration timescales are shorter than they would be if transient evolution were considered.

The million-year 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 or interglacial period (Lai & Huppert, 2023). Therefore, periodic climate disturbances in the Quaternary may have caused persistent drainage reorganization in mountain ranges that have alternately been shaped by glacial and fluvial erosion.

5 Conclusions

Using an analytic model of a steady-state glacial profile, we quantified topographic asymmetry caused by asymmetric glaciation. Our results show that, under analogous cross-divide precipitation contrasts, glacial erosion creates higher degrees of topographic asymmetry than fluvial erosion at steady state. The timescales of divide migration are several million years - much longer than typical periods of glacial-interglacial cycles. This implies that intermittent glaciations can induce persistent divide migration and drainage reorganization in glaciated mountain ranges.

Open Research Section

The Sliding Ice Incision Model is available at `https://doi.org/10.5281/zenodo.4269433`. The Python scripts used to calculate results presented in this work is archived at `https://github.com/laijingtao/glacial_divide_stability_GRL`.

Acknowledgments

J. Lai is supported by funding from the European Union's Marie Skłodowska-Curie Actions Postdoctoral Fellowship No. 101064307. We thank Jean Braun for helpful discussion. We used ChatGPT for proofreading.

References

Beeson, H. W., McCoy, S. W., & Keen-Zebert, A. (2017). Geometric disequilibrium of river basins produces long-lived transient landscapes. *Earth and Planetary Science Letters*, *475*, 34–43. doi: 10.1016/j.epsl.2017.07.010

Braun, J., Zwartz, D., & Tomkin, J. H. (1999). A new surface-processes model combining glacial and fluvial erosion. *Annals of Glaciology*, *28*, 282–290. doi: 10.3189/172756499781821797

Clift, P. D., & Blusztajn, J. (2005). Reorganization of the western Himalayan river system after five million years ago. *Nature*, *438*(7070), 1001–1003. doi: 10.1038/nature04379

Cook, S. J., Swift, D. A., Kirkbride, M. P., Knight, P. G., & Waller, R. I. (2020). The empirical basis for modelling glacial erosion rates. *Nature Communications*, *11*(1), 759. doi: 10.1038/s41467-020-14583-8

Dahl, S. O., & Nesje, A. (1992). Paleoclimatic implications based on equilibrium-line altitude depressions of reconstructed Younger Dryas and Holocene cirque glaciers in inner Nordfjord, western Norway. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *94*(1), 87–97. doi: 10.1016/0031-0182(92)90114-K

Dahlquist, M. P., West, A. J., & Li, G. (2018). Landslide-driven drainage divide migration. *Geology*, *46*(5), 403–406. doi: 10.1130/G39916.1

Deal, E., & Prasicek, G. (2021). The Sliding Ice Incision Model: A New Approach to Understanding Glacial Landscape Evolution. *Geophysical Research Letters*, *48*(1), 1–15. doi: 10.1029/2020GL089263

Dortch, J. M., Owen, L. A., Schoenbohm, L. M., & Caffee, M. W. (2011). Asymmetrical erosion and morphological development of the central Ladakh Range, northern India. *Geomorphology*, *135*(1-2), 167–180. doi: 10.1016/j.geomorph.2011.08.014

Egholm, D. L., Nielsen, S. B., Pedersen, V. K., & Lesemann, J. E. (2009). Glacial effects limiting mountain height. *Nature*, *460*(13), 884–887. doi: 10.1038/nature08263

Evans, I. S. (1977). World-Wide Variations in the Direction and Concentration of Cirque and Glacier Aspects. *Geografiska Annaler: Series A, Physical Geography*, *59*(3-4), 151–175. doi: 10.1080/04353676.1977.11879949

Evans, I. S., & Cox, N. J. (2005). Global variations of local asymmetry in glacier altitude: Separation of north–south and east–west components. *Journal of Glaciology*, *51*(174), 469–482. doi: 10.3189/172756505781829205

Ferrier, K. L., Huppert, K. L., & Perron, J. T. (2013). Climatic control of bedrock river incision. *Nature*, *496*(7444), 206–209. doi: 10.1038/nature11982

Forte, A. M., & Whipple, K. X. (2018). Criteria and tools for determining drainage divide stability. *Earth and Planetary Science Letters*, *493*, 102–117. doi: 10.1016/j.epsl.2018.04.026

Foster, D., Brocklehurst, S. H., & Gawthorpe, R. L. (2010). Glacial-topographic interactions in the Teton Range, Wyoming. *Journal of Geophysical Research*, *115*(F1), F01007. doi: 10.1029/2008JF001135

Gilbert, G. K. (1904). Systematic Asymmetry of Crest Lines in the High Sierra of California. *The Journal of Geology*, *12*(7), 579–588. doi: 10.1086/621182

Hack, J. T. (1957). *Studies of longitudinal stream profiles in Virginia and Maryland* (Vol. 294-B). Washington DC: US Government Printing Office.

He, C., Yang, C.-J., Turowski, J. M., Rao, G., Roda-Boluda, D. C., & Yuan, X.-P. (2021). Constraining tectonic uplift and advection from the main drainage divide of a mountain belt. *Nature Communications*, *12*(1), 544. doi: 10.1038/s41467-020-20748-2

Herman, F., Beyssac, O., Brughelli, M., Lane, S. N., Leprince, S., Adatte, T., ... Cox, S. C. (2015). Erosion by an Alpine glacier. *Science*, *350*(6257), 193–195. doi: 10.1126/science.aab2386

Herman, F., Braun, J., Deal, E., & Prasicek, G. (2018). The Response Time of Glacial Erosion. *Journal of Geophysical Research: Earth Surface*, *123*(4), 801–

817. doi: 10.1002/2017JF004586

Herman, F., De Doncker, F., Delaney, I., Prasicek, G., & Koppes, M. (2021). The impact of glaciers on mountain erosion. *Nature Reviews Earth & Environment*. doi: 10.1038/s43017-021-00165-9

Hoorn, C., Wesselingh, F. P., Ter Steege, H., Bermudez, M. A., Mora, A., Sevink, J., ... Antonelli, A. (2010). Amazonia Through Time: Andean Uplift, Climate Change, Landscape Evolution, and Biodiversity. *Science*, *330*(6006), 927–931. doi: 10.1126/science.1194585

Howard, A. D., & Kerby, G. (1983). Channel changes in badlands. *Geological Society of America Bulletin*, *94*(6), 739. doi: 10.1130/0016-7606(1983)94⟨739:CCIB⟩2.0.CO;2

Hu, K., Fang, X., Ferrier, K. L., Granger, D. E., Zhao, Z., & Ruetenik, G. A. (2021). Covariation of cross-divide differences in denudation rate and χ: Implications for drainage basin reorganization in the Qilian Shan, northeast Tibet. *Earth and Planetary Science Letters*, *562*, 116812. doi: 10.1016/j.epsl.2021.116812

Humphrey, N. F., & Raymond, C. F. (1994). Hydrology, erosion and sediment production in a surging glacier: Variegated Glacier, Alaska, 1982–83. *Journal of Glaciology*, *40*(136), 539–552. doi: 10.3189/S0022143000012429

Hutter, K. (1983). *Theoretical Glaciology.* Dordrecht, Netherlands: D. Reidel Publishing Company. doi: 10.1007/978-94-015-1167-4

Koppes, M., Hallet, B., Rignot, E., Mouginot, J., Wellner, J. S., & Boldt, K. (2015). Observed latitudinal variations in erosion as a function of glacier dynamics. *Nature*, *526*(7571), 100–3. doi: 10.1038/nature15385

Lai, J., & Huppert, K. (2023). Asymmetric glaciation, divide migration, and postglacial fluvial response times in the Qilian Shan. *Geology*, *51*(9), 860–864. doi: 10.1130/G51086.1

Leith, K., Moore, J. R., Amann, F., & Loew, S. (2014). Subglacial extensional fracture development and implications for Alpine Valley evolution. *Journal of Geophysical Research: Earth Surface*, *119*(1), 62–81. doi: 10.1002/2012JF002691

Margason, A. A., Anders, A. M., Conrick, R. J. C., & Roe, G. H. (2023). Spatially coherent variability in modern orographic precipitation produces asymmetric paleo-glacier extents in flowline models: Olympic Mountains, USA. *Earth Surface Dynamics*, *11*(5), 849–863. doi: 10.5194/esurf-11-849-2023

Olson, M., & Rupper, S. (2019). Impacts of topographic shading on direct solar radiation for valley glaciers in complex topography. *The Cryosphere*, *13*(1), 29–40. doi: 10.5194/tc-13-29-2019

Oskin, M., & Burbank, D. W. (2005). Alpine landscape evolution dominated by cirque retreat. *Geology*, *33*(12), 933. doi: 10.1130/G21957.1

Prasicek, G., Hergarten, S., Deal, E., Herman, F., & Robl, J. (2020). A glacial buzzsaw effect generated by efficient erosion of temperate glaciers in a steady state model. *Earth and Planetary Science Letters*, *543*, 116350. doi: 10.1016/j.epsl.2020.116350

Richardson, P. W., Perron, J. T., Miller, S. R., & Kirchner, J. W. (2020). Unraveling the Mysteries of Asymmetric Topography at Gabilan Mesa, California. *Journal of Geophysical Research: Earth Surface*, *125*(7), e2019JF005378. doi: 10.1029/2019JF005378

Schildgen, T. F., van der Beek, P. A., D'Arcy, M., Roda-Boluda, D., Orr, E. N., & Wittmann, H. (2022). Quantifying drainage-divide migration from orographic rainfall over geologic timescales: Sierra de Aconquija, southern Central Andes. *Earth and Planetary Science Letters*, *579*, 117345. doi: 10.1016/j.epsl.2021.117345

Shi, F., Tan, X., Zhou, C., & Liu, Y. (2021). Impact of asymmetric uplift on mountain asymmetry: Analytical solution, numerical modeling, and natural examples. *Geomorphology*, *389*, 107862. doi: 10.1016/j.geomorph.2021.107862

Shuster, D. L., Ehlers, T. A., Rusmoren, M. E., & Farley, K. A. (2005). Rapid Glacial Erosion at 1.8 Ma Revealed by 4He/3He Thermochronometry. *Science*, *310*(5754), 1668–1670. doi: 10.1126/science.1118519

Smith, T., & Bookhagen, B. (2021). Climatic and Biotic Controls on Topographic Asymmetry at the Global Scale. *Journal of Geophysical Research: Earth Surface*, *126*(1), e2020JF005692. doi: 10.1029/2020JF005692

Whipple, K. X., Forte, A. M., DiBiase, R. A., Gasparini, N. M., & Ouimet, W. B. (2017). Timescales of landscape response to divide migration and drainage capture: Implications for the role of divide mobility in landscape evolution. *Journal of Geophysical Research: Earth Surface*, *122*(1), 248–273. doi: 10.1002/2016JF003973

Whipple, K. X., & Tucker, G. E. (1999). Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs. *Journal of Geophysical Research: Solid Earth*, *104*(B8), 17661–17674. doi: 10.1029/1999JB900120

Willett, S. D., & Brandon, M. T. (2002). On steady states in mountain belts. *Geology*, *30*(2), 175. doi: 10.1130/0091-7613(2002)030⟨0175:OSSIMB⟩2.0.CO;2

Willett, S. D., McCoy, S. W., Perron, J. T., Goren, L., & Chen, C.-Y. (2014). Dynamic Reorganization of River Basins. *Science*, *343*(6175), 1248765–1248765. doi: 10.1126/science.1248765

Figure 1.

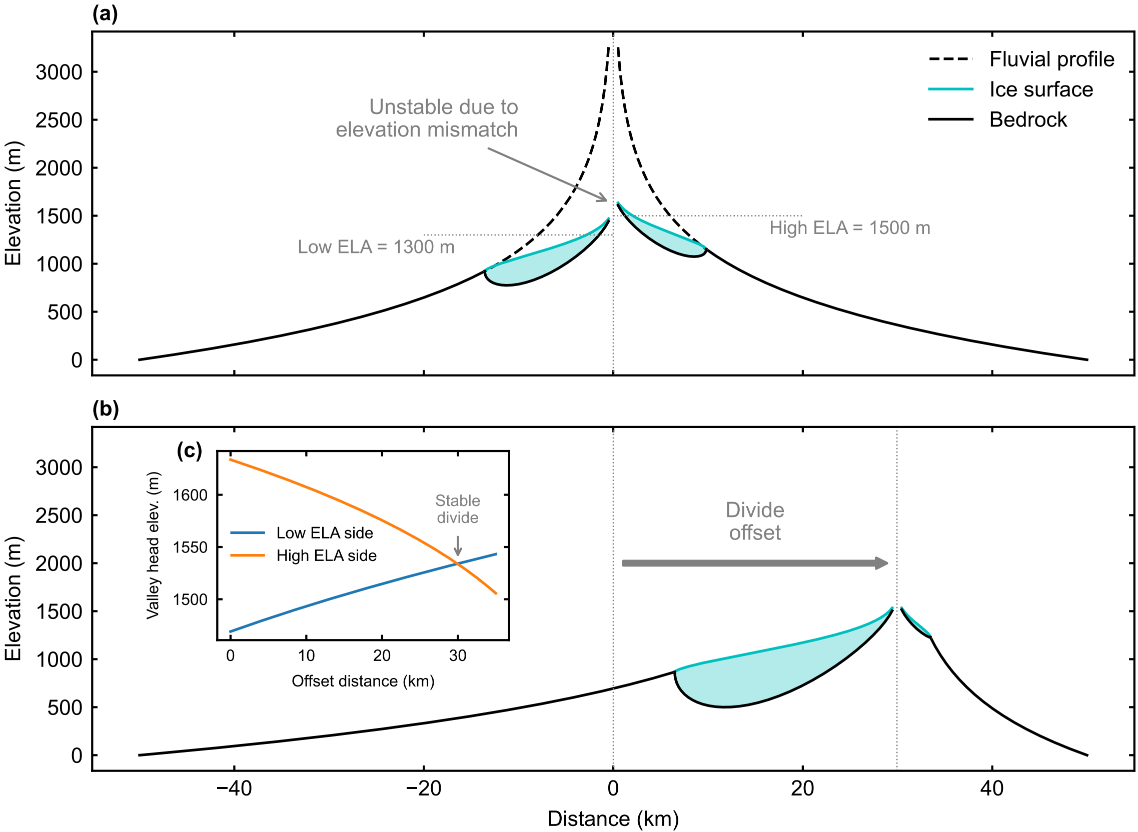

(a)
Fluvial profile
Ice surface
Bedrock
Unstable due to
elevation mismatch
Low ELA = 1300 m
High ELA = 1500 m
Elevation (m)
3000
2500
2000
1500
1000
500
0
(b)
(c)
Valley head elev. (m)
1600
1550
1500
Low ELA side
High ELA side
Stable
divide
0
10
20
30
Offset distance (km)
Divide
offset
−40
−20
0
20
40
Distance (km)

Figure 2.

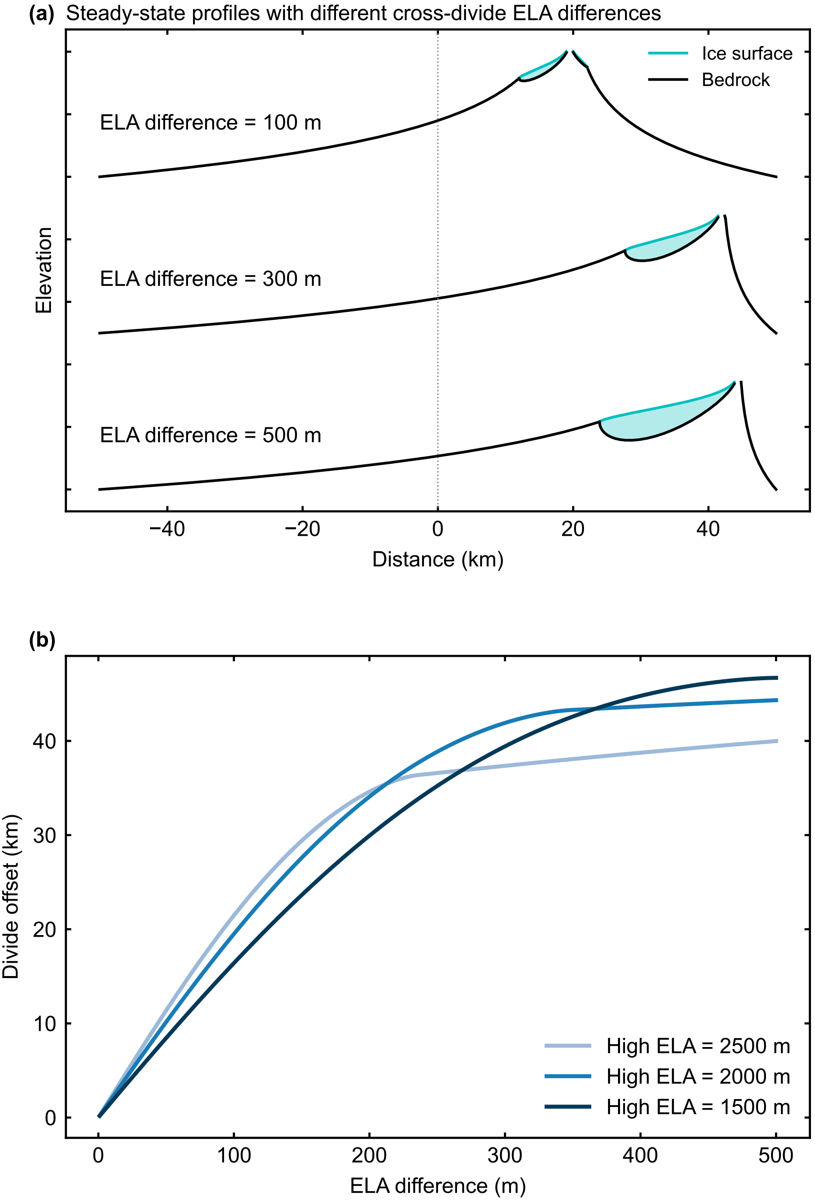
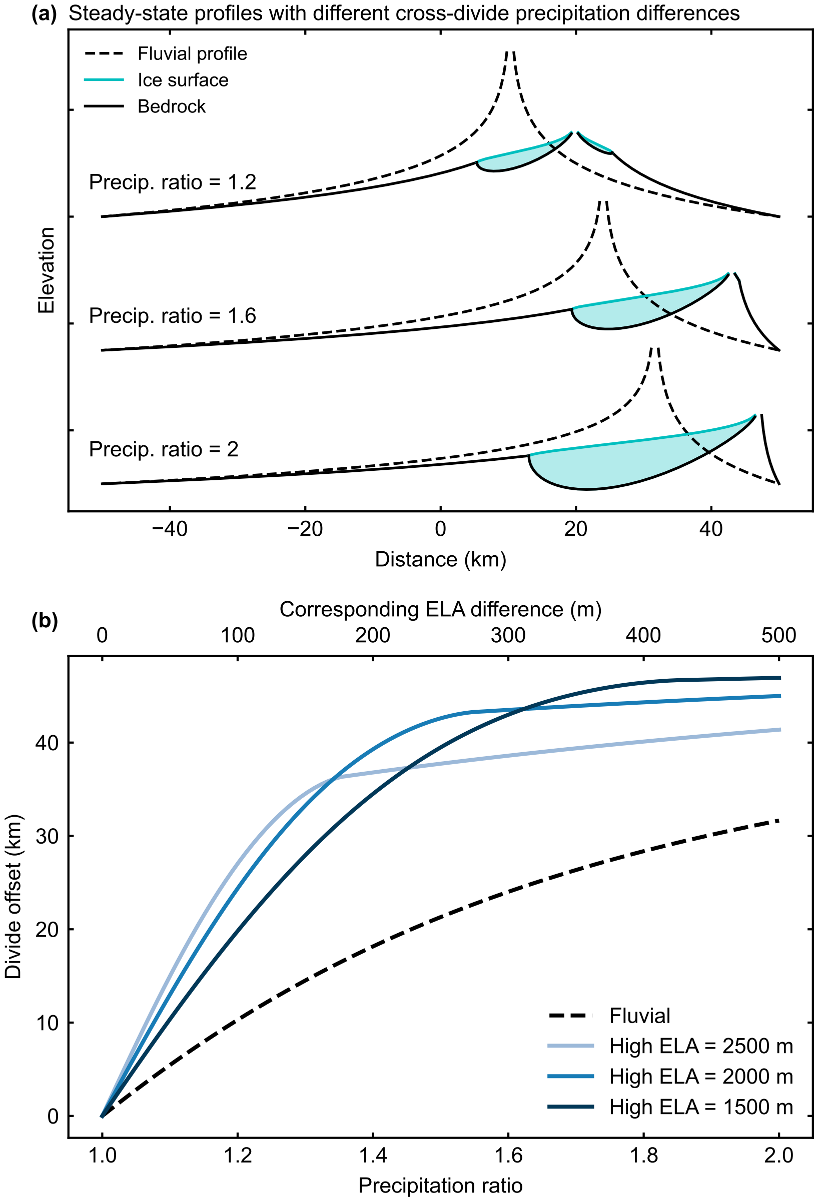
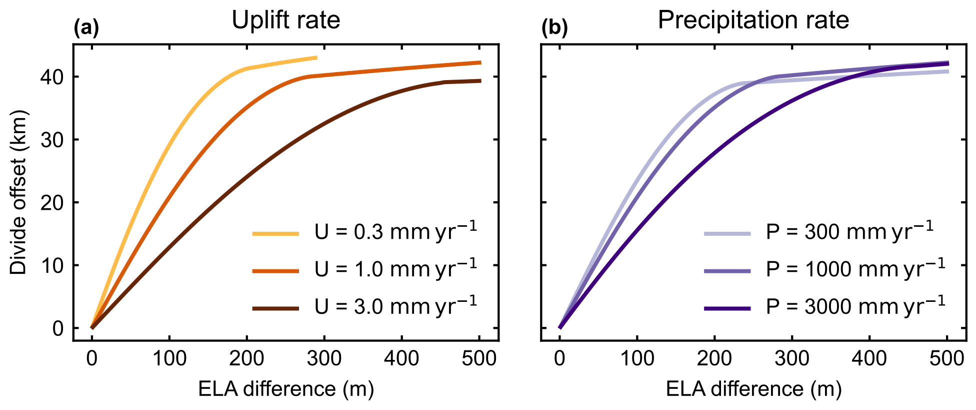

(a) Steady-state profiles with different cross-divide ELA differences
Ice surface
Bedrock
ELA difference = 100 m
ELA difference = 300 m
ELA difference = 500 m
Elevation
−40
−20
0
20
40
Distance (km)
(b)
Divide offset (km)
0
10
20
30
40
0
100
200
300
400
500
ELA difference (m)
High ELA = 2500 m
High ELA = 2000 m
High ELA = 1500 m

Figure 3.



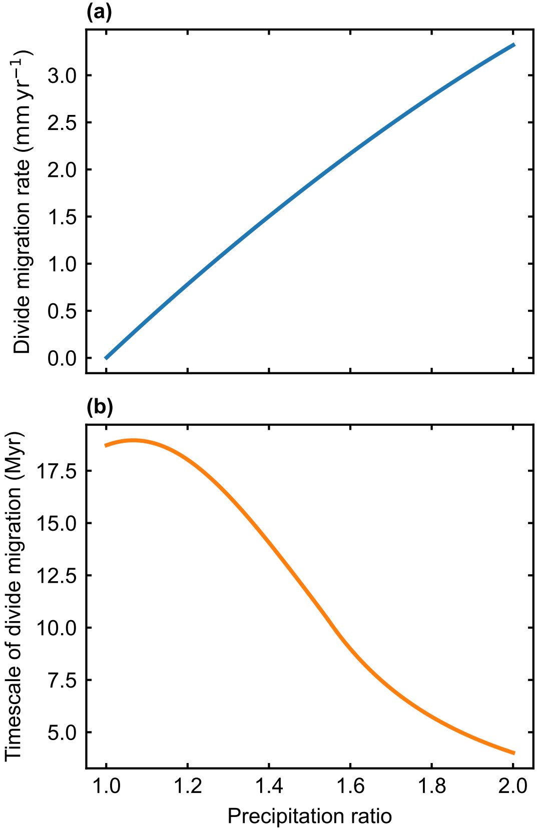
(a) Steady-state profiles with different cross-divide precipitation differences
Fluvial profile
Ice surface
Bedrock
Precip. ratio = 1.2
Precip. ratio = 1.6
Precip. ratio = 2
Elevation
−40
−20
0
20
40
Distance (km)
(b)
Corresponding ELA difference (m)
0
100
200
300
400
500
Divide offset (km)
0
10
20
30
40
Fluvial
High ELA = 2500 m
High ELA = 2000 m
High ELA = 1500 m
1.0
1.2
1.4
1.6
1.8
2.0
Precipitation ratio

Figure 4.



(a)
Uplift rate
(b)
Precipitation rate
Divide offset (km)
ELA difference (m)
U = 0.3 mm yr⁻¹
U = 1.0 mm yr⁻¹
U = 3.0 mm yr⁻¹
P = 300 mm yr⁻¹
P = 1000 mm yr⁻¹
P = 3000 mm yr⁻¹
0
10
20
30
40
100
200
300
400
500

Figure 5.


(a)
Divide migration rate (mm yr^{-1})
0.0
0.5
1.0
1.5
2.0
2.5
3.0
(b)
Timescale of divide migration (Myr)
5.0
7.5
10.0
12.5
15.0
17.5
1.0
1.2
1.4
1.6
1.8
2.0
Precipitation ratio