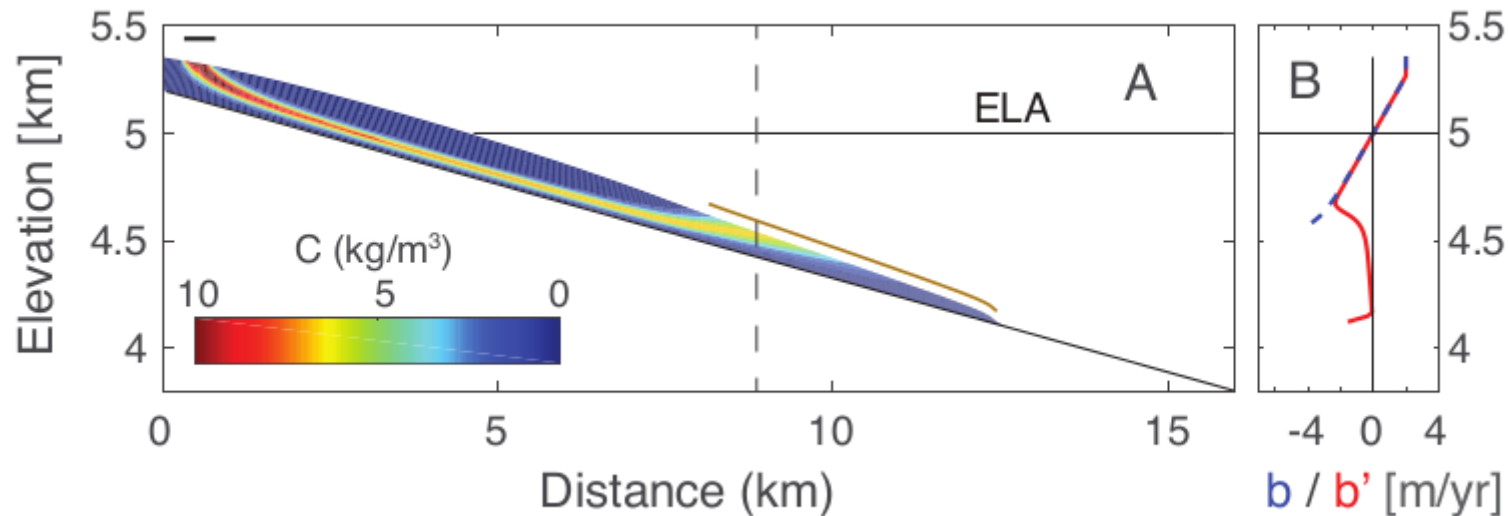


Geomorphic feedbacks on the moraine record



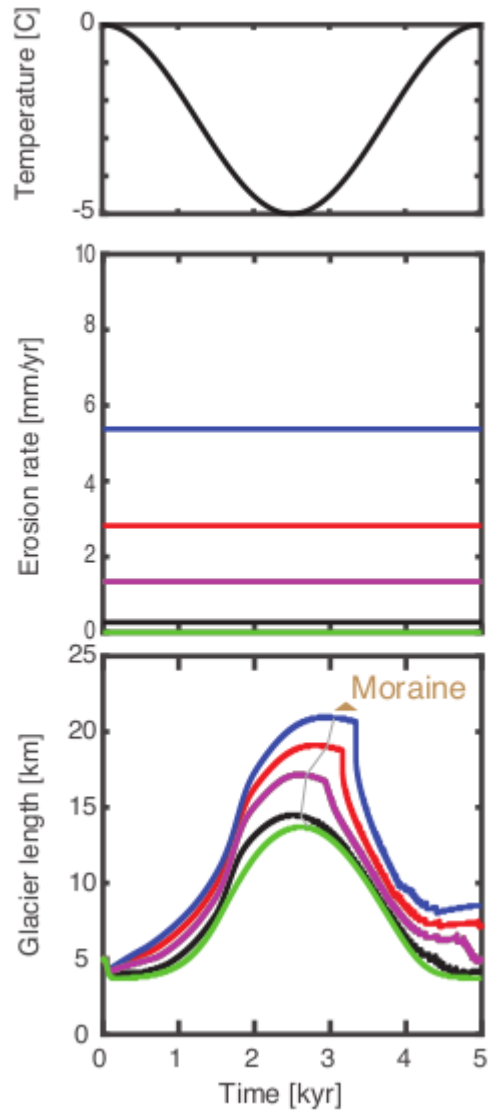
► **Glaciers** grow and shrink primarily due to **climate change**.

► But on many valley glaciers rocky **debris reduces melt rates** and extends glaciers.

► We modulate hillslope erosion with temperature by tracking **frost-cracking** damage (Rempel et al., 2016).

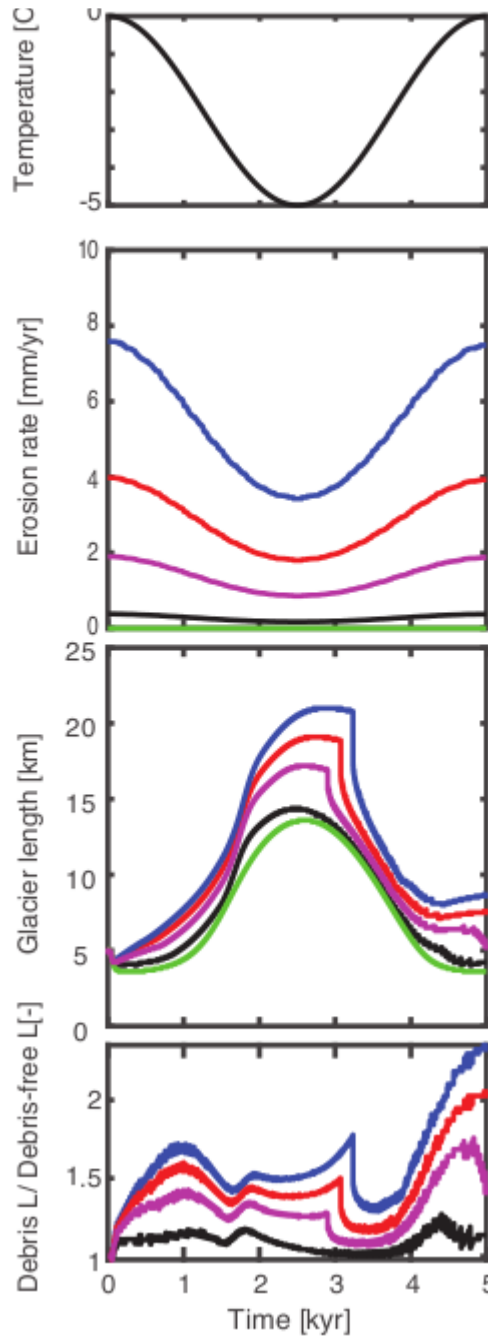
► We use a **numerical model** of a debris-covered glacier to explore feedbacks between climate, erosion, and ice.

Steady erosion rates

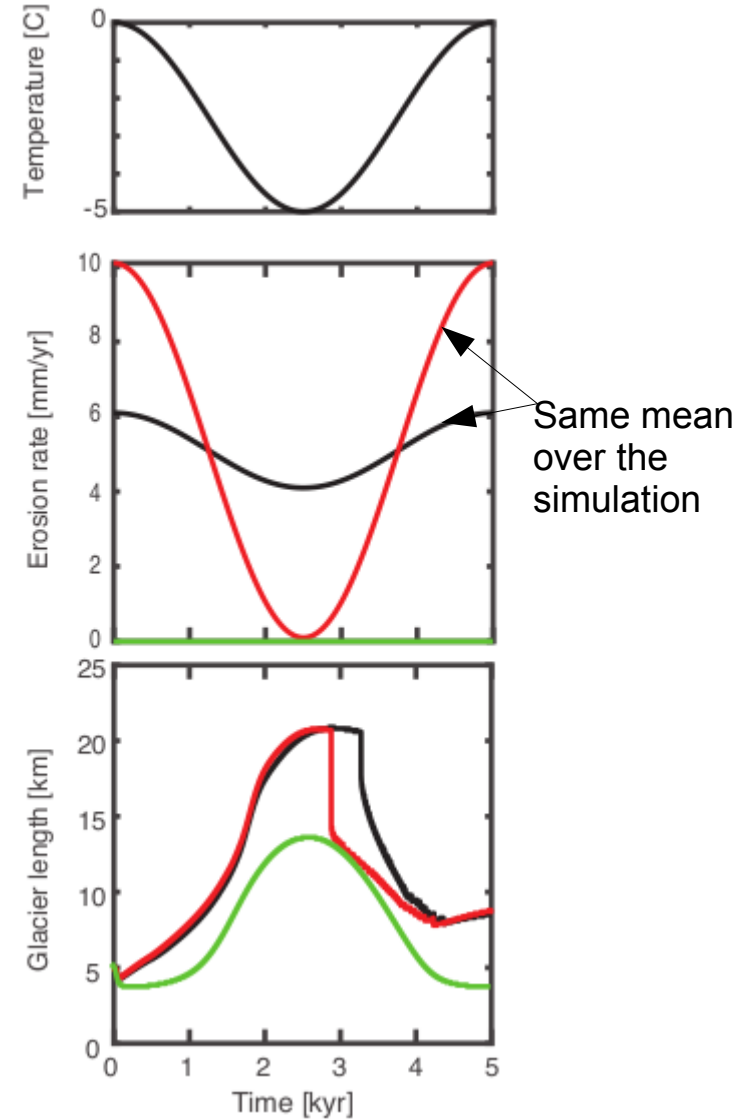


Debris tends to delay the timing of moraine formation. Debris allows glaciers to remain at maximum extents for longer.

Frost-cracking modulated

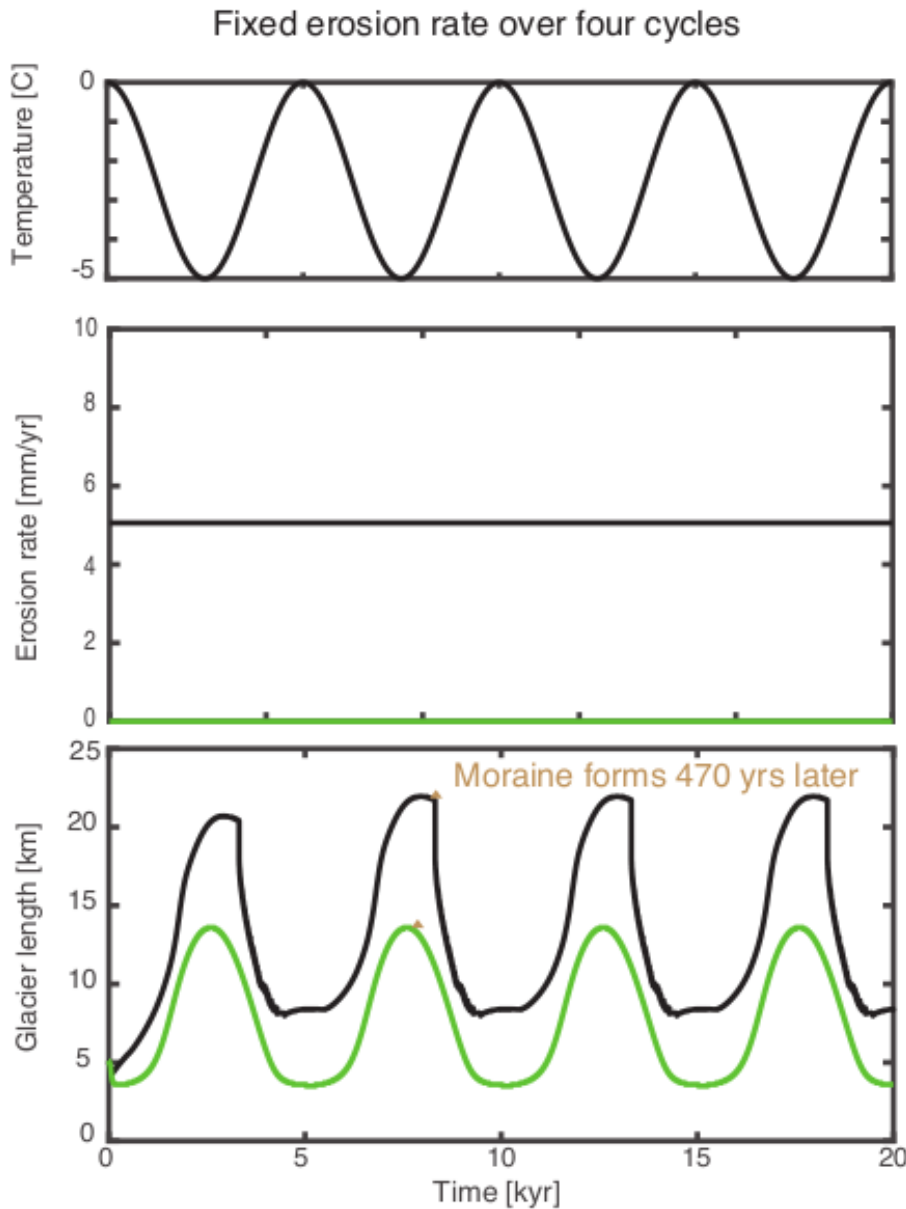


Frost-cracking modulated



The amplitude of erosion affects when the glacier retreats as well as the timing of moraine emplacement

Steady erosion over four climate cycles



Length enhancement is larger in cooling climates than in warming climates. This occurs because melt rate reduction from both debris and low temperatures expand the glacier.

As temperatures rise much of the debris cover is removed from the glacier surface as the terminus retreats. In spite of rising temperatures, debris cover tends to extend the glacier. In this simulation temperature rise dominates the length-enhancing effect of surface debris.

Rempel, A. W., Marshall, J. A. and Roering, J. J.: Modeling relative frost weathering rates at geomorphic scales, *Earth and Planetary Science Letters*, 453, 87–95, doi:10.1016/j.epsl.2016.08.019, 2016.