LETTERS

# Glacial effects limiting mountain height

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**The height of mountain ranges reflects the balance between tectonic rock uplift, crustal strength and surface denudation. Tectonic deformation and surface denudation are interdependent, however, and feedback mechanisms—in particular, the potential link to climate—are subjects of intense debate[1,2]. Spatial variations in fluvial denudation rate caused by precipitation gradients are known to provide first-order controls on mountain range width, crustal deformation rates and rock uplift[3,4]. Moreover, limits to crustal strength[5] are thought to constrain the maximum elevation of large continental plateaus, such as those in Tibet and the central Andes. There are indications that the general height of mountain ranges is also directly influenced by the extent of glaciation through an efficient denudation mechanism known as the glacial buzzsaw[6–9]. Here we use a global analysis of topography and show that variations in maximum mountain height correlate closely with climate-controlled gradients in snowline altitude for many high mountain ranges across orogenic ages and tectonic styles. With the aid of a numerical model, we further demonstrate how a combination of erosional destruction of topography above the snowline by glacier-sliding and commensurate isostatic landscape uplift caused by erosional unloading can explain observations of maximum mountain height by driving elevations towards an altitude window just below the snowline. The model thereby self-consistently produces the hypsometric signature of the glacial buzzsaw, and suggests that differences in the height of mountain ranges mainly reflect variations in local climate rather than tectonic forces.**

Distinctive alpine landforms, such as broad 'U'-shaped, flat-floored valleys, hanging valleys, cirques, horns and knife-edged ridges (arêtes), are considered the fingerprints of glacial erosion. These glacial landforms exist in most of Earth's mountain chains, produced by present and past glaciers. A majority of these landforms are associated with pronounced topographic relief consisting of over-steepened valley sides, headwalls and near-orthogonal tributary junctions often occupied by spectacular waterfalls. Perhaps not surprisingly, glaciations have accordingly been assumed to increase average relief mainly by incising valley systems, leaving high elevation peaks and hillslopes almost unaffected, and producing significant isostatically driven peak uplift[10].

However, it has recently been discovered that glaciated orogens in the Himalayas[6], the Andes[7], the Sierra Nevada (USA)[11] and the Cascade Range[8] hold a striking coincidence of snowline altitudes, glacier equilibrium line altitudes (ELA) and elevations with a high proportion of surface area, suggesting that operation of a glacial buzzsaw denudation mechanism may be effective in reducing surface topography above the snowline and concentrating it at the snowline.

Apatite $^4He/^3He$ ratio and (U–Th)/He thermochronometry studies from British Columbia[12] and the St Elias orogen in Alaska[13] support the notion of rapid glacial erosion at altitudes near and above the snowline, and indicate that climatically controlled snowline lowering dramatically increased average erosion rates during the late Cenozoic.

The geomorphic signature of the glacial buzzsaw is a concentration of surface area at elevations corresponding to the glacial ELA or the snowline[6–9,11], which roughly coincide for temperate glaciers[14]. In hypsometric distributions (Fig. 1a), this reveals itself as a local maximum (representing a high proportion of surface area) at an altitude corresponding to the snowline[6,15]. To explore the prevalence of the glacial buzzsaw, we thus analysed the global distribution of hypsometric maxima (Fig. 1b) and surface area (Fig. 1c) using the Shuttle Radar Topography Mission[16] (SRTM) digital elevation models (DEMs) and compared this with observations of modern and Last Glacial Maximum (LGM) snowline altitudes[17,18]. We focus on the latitude dependence because the variation in snowline altitude is larger with latitude than with longitude (or with time); see Supplementary Figs 1–4 for more details of the analysis.

The analysis first reveals how only little surface area and practically no hypsometric maxima occur at elevations above the local modern snowline altitude (Fig. 1b and c). Second, below the snowline, surface area is concentrated in readily recognizable tectonically uplifted plateaus and near sea level, where alluvial plains increasingly dominate as they grade to sea level (Fig. 1c). The modern snowline seems to closely follow the $10^{-6}$ contour of normalized surface area (the blue end of the colour scale in Fig. 1c), emphasizing its influence on high-altitude hypsometry.

When a DEM tile has topography above the snowline, its highest hypsometric maximum generally exists between the modern and LGM snowlines (Fig. 2). This pattern is recognized globally in every mountain range with sufficient height to intersect the LGM snowline (Supplementary Fig. 4). Hence, the abundance of hypsometric maxima just below the modern snowline and the absence of hypsometric maxima above the snowline are largely independent of tectonic uplift rate, lithology and general tectonic setting. For example, the Himalayas are in an intra-continental setting caused by continent–continent collision between India and Asia, whereas the high topography in western North and South America and in New Zealand is adjacent to oceans and caused by subduction and related volcanism. Yet, all show similar correlation between the distribution of hypsometric maxima and the local snowline altitude.

It further appears that glacial erosion controls the maximum height of mountains, as most summit elevations are confined to altitudes $<$1,500 m above the local snowline (Fig. 2). Although some of the highest peaks are evidently not included in the analysis owing to data gaps, this general trend suggests that glacial erosion restricts the height of mountains by limiting the relief that can be maintained between mountain peaks and the snowline[1]. The recorded outliers (Fig. 2) represent solitary peaks of primarily volcanic origin and most exist in the Andes, implying that formation and ongoing build-up of high volcanoes can outpace glacial buzzsaw denudation. Notable exceptions to the trend also exist in the Transantarctic Mountains outside the data set where a reduction or even non-existence of the glacial buzzsaw mechanism is likely, as non-eroding polar glaciers (frozen at the bed) dominate where the ice cover is relatively thin[19].

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