Feature

Everest's thinning glaciers: implications for tourism and mountaineering

Glacier mass loss in the Everest region of Nepal is accelerating in response to a warming climate, which is a trend observed across the central and eastern Himalaya. Thinning glaciers and the development of supraglacial (surface) ponds and large glacial lakes will increasingly restrict access to glacier surfaces and will affect popular trekking routes and mountaineering activities in the region. Through quantifying glacier accessibility and supraglacial pond expansion, we estimate that the Kongma La Pass trail across the Khumbu Glacier is likely to be impassable by 2020 due to supraglacial pond expansion and glacier thinning, and will require significant re-routing. An estimated 197 649 227 m^3 of ice melted over the period 1984–2015 on the Khumbu Glacier. Additionally, expert opinion from Everest mountaineers suggest that rockfall activity is likely to increase in the high-mountain environment as snow and ice melts from mountain slopes, requiring changes to climbing routes on the world's highest peaks. Similarly, route difficulty will be affected by changing monsoon precipitation patterns, which determines windows of opportunity for ascents, and the distribution and quantity of snowfall. We conclude that increased collaboration between the scientific, local, and mountaineering communities offers mutual benefits for data collection and dissemination, and we identify key areas that should be investigated further.

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Many Himalayan glaciers feature a mantle of debris that can be several metres thick. This debris layer is composed of clasts of various size, ranging from fine silts to large boulders, which is predominantly sourced from the surrounding mountains and transported down-valley by glacier flow. The debris insulates the ice beneath when exceeding a thickness of several centimetres, but can also amplify ice melt if the debris layer is very thin (<3 cm), due to the preferential absorption and transfer of solar radiation by the much darker rock and sediment. The thickness of this debris layer is spatially heterogeneous, which leads to variable melt rates across the glacier surface and the development of an uneven surface topography (Fig. 1). Supraglacial ponds (Fig. 1a) and ice cliffs (Fig. 1b) on the surface of glaciers are considered 'hot-spots' of melt, the magnitude of which is revealed when using fine-resolution imagery and digital elevation models (DEMs) of difference to quantify surface elevation changes.

Ice cliffs retreat on the order of several to tens of metres each year, depending upon the presence of an adjacent supraglacial pond, which increases melt through thermo-erosion at the cliff base. Supraglacial ponds with adjacent ice cliffs are highly turbid, which is caused by debris influx from cliff-tops as they retreat. High pond turbidity increases the absorption of solar radiation and this thermal energy is transmitted to the underlying glacier ice, or inside the glacier during drainage if the pond intercepts an englacial conduit. Ponds therefore enhance glacier melt and promote the formation of new ice cliffs and pond basins as englacial conduits collapse to leave depressions in the glacier surface, forming a positive feedback that often leads to the development of large, moraine-impounded lakes.

Large glacial lakes are a concern to downstream communities and infrastructure including hydropower

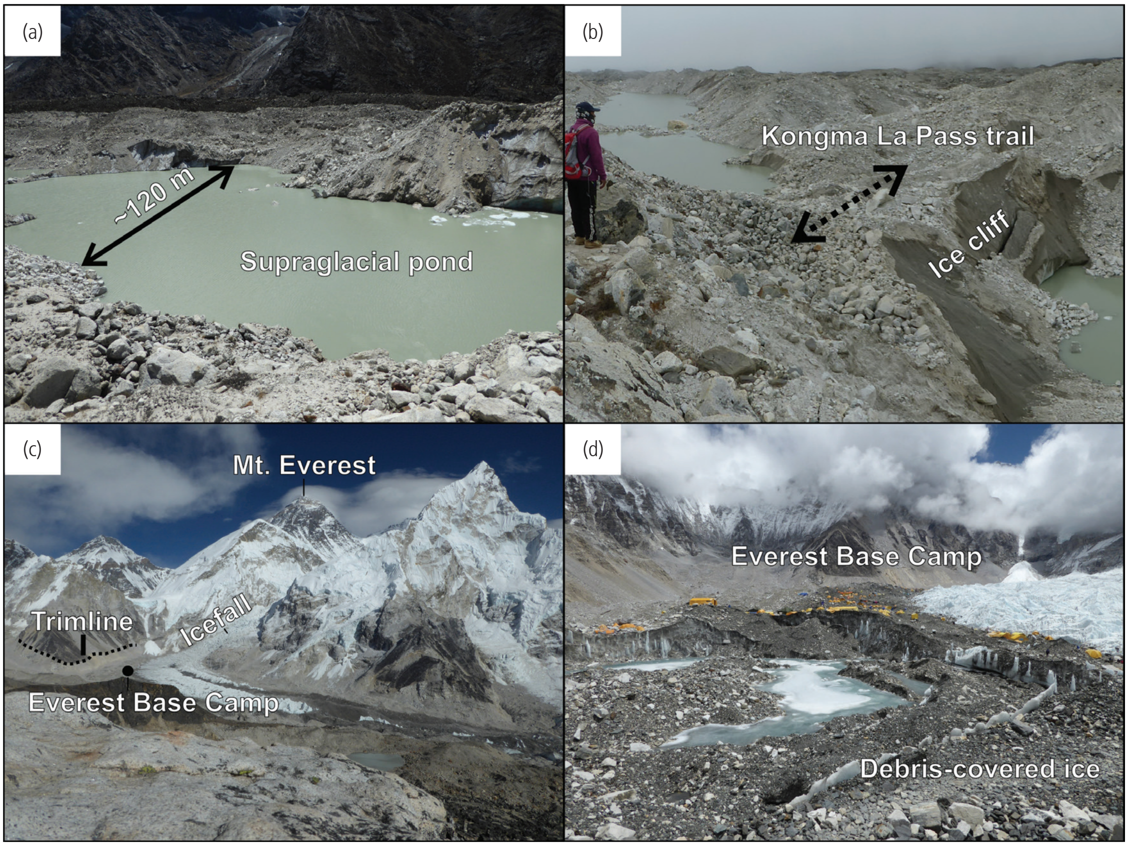

Fig. 1. Surface features on the debris-covered Khumbu Glacier including: **a.** supraglacial ponds that can exceed tens of metres in depth, **b.** the Kongma La Pass trail passing between two supraglacial ponds and a retreating ice cliff, and **c,d.** views of Everest Base Camp and the transition from clean-ice to debris-covered ice as the glacier descends the Khumbu Icefall.

facilities, since the lakes are dammed by moraines composed of glacially derived debris of unknown stability. Avalanches or rock falls into the lake, or a destabilizing of the dam via an event such as an earthquake, can initiate catastrophic drainage events termed glacial lake outburst floods (GLOFs) where large volumes of water flow rapidly downstream. Additionally, the internal glacier hydrology can become re-organized or blocked as the surface lowers and sudden drainage can occur without warning, causing smaller outburst flood events.

Recent studies have primarily focused on how the disappearance of glaciers will affect the number and size of glacial lakes, with associated GLOF hazards; and a change in the magnitude and seasonality of river flows, with associated implications for downstream irrigation, sanitation and hydropower use. However, the implications of glacier disappearance for tourism and mountaineering activities remain unexplored, despite their importance for socio-economic development in glacierized regions (e.g. the Sagarmatha and Annapurna National Parks in Nepal). Glacier surfaces that are becoming increasingly disconnected from the surrounding topography makes access ever more difficult for trekking trails that use the glaciers as shortcuts across valleys (e.g. Fig. 2). Additionally, hazards threatening mountaineering activities, such as avalanches and rockfalls, are likely to increase as mountain slopes become snow and ice-free.

In this study, we explore the implications of glacier thinning and climate change on trekking and mountaineering activities in Sagarmatha National Park in Nepal, which is visited by tens of thousands of tourists each year. We present an analysis of glacier surface lowering, glacier velocity, and supraglacial pond expansion, to determine how glacier dynamics and accessibility is changing over time. Additionally, we relate the views of three expert mountaineers to describe changing trends at high altitude, which is generally not accessed or well documented by the scientific community.

Tourism in Sagarmatha National Park

The tourist economy in Sagarmatha National Park now eclipses traditional farming activities and has brought employment opportunities, electricity and internet access to remote mountain communities. However, this also brings local environmental pressures as tourist numbers increase, with higher expectations regarding accommodation, washing-facilities and reliable internet access.

Visitors to the national park include tourists trekking along popular trails, often to visit Everest Base Camp (EBC), and mountaineers accessing Mount Everest and other high-altitude peaks. Trekking trails often pass over glaciers including the routes

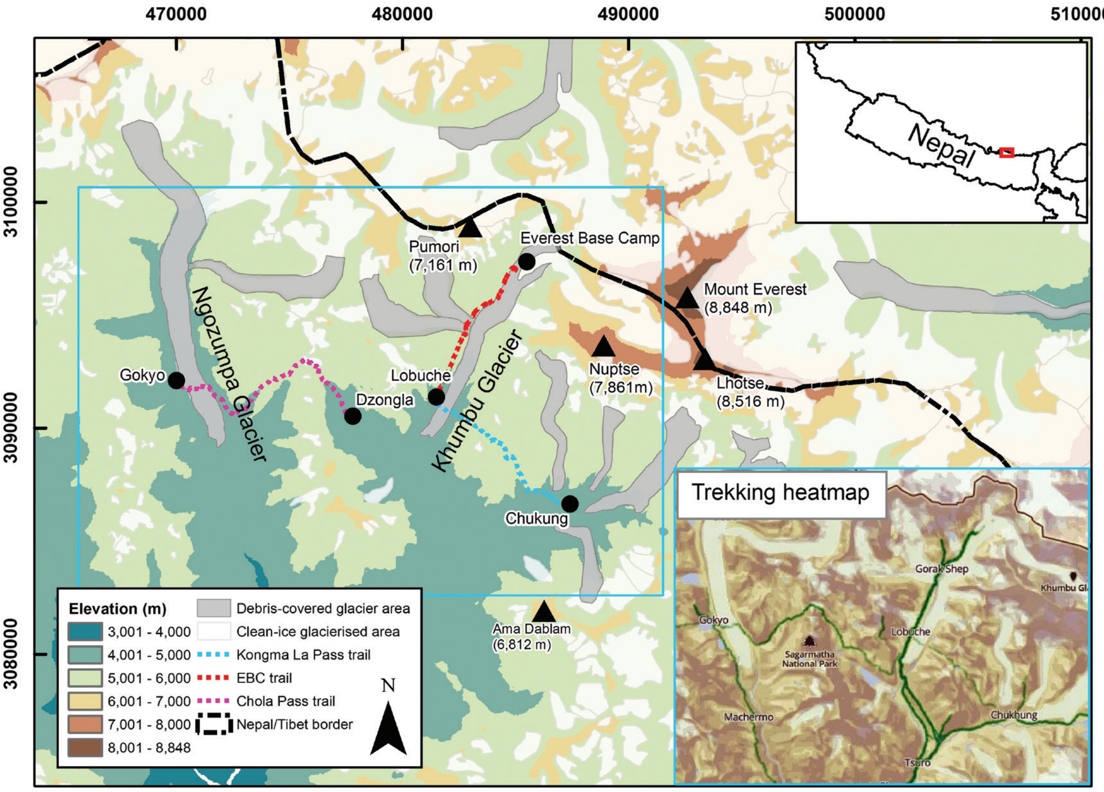

Fig. 2. Debris-covered glaciers around Mount Everest and popular trekking trails. The trekking heatmap is derived from publically available Suunto global positioning system (GPS) watch data.

of the Kongma La Pass and the Chola Pass trails, which cross the Khumbu and Ngozumpa glaciers respectively (Fig. 2). However, these routes are frequently diverted in response to challenges posed by the increasing elevation difference between the Little Ice Age (LIA) glacial moraines (formed 400–700 years ago) and the contemporary glacier surface (Fig. 3a), and the expansion of supraglacial ponds. The increasing prevalence of GPS-enabled watches and smartphones with integrated barometers means that trekking journeys are often recorded along with time-stamps and altitude profiles, which are frequently made available online (e.g. Fig. 2). These data offer new opportunities for crowdsourcing data on popular trekking trails, including how route selection changes through time, and how the elevation of the glacier surface is changing.

Glacier thinning

Surface lowering is perhaps the most pronounced evidence of glaciers out of equilibrium with current climatic conditions and is visible from the vertical offset between the LIA moraines and the present-day glacier surface (Fig. 3a). Glacier surface lowering can be quantified by comparing multi-temporal DEMs derived from satellite imagery. On heavily debris-covered glaciers the maximum surface lowering occurs mid-way up the glacier where the debris-cover is thinner; however, localized hot-spots of melt are visible around ice cliffs and supraglacial ponds. Quantifying the magnitude of melt is important for predicting the longevity of glaciers in the region, and subsequent change in river runoff. Additionally, the distribution of melt across a glacier surface reveals the likelihood of glacial lake development, since meltwater can effectively pond on low gradient glaciers, which allows individual ponds to coalesce.

Using DEMs from 1984 and 2015 the surface elevation change of the debris-covered Khumbu Glacier was calculated and was used to estimate the volume of ice lost. At Lobuche, the average surface elevation change 1984–2015 was –15.8 m, or –0.51 m/yr (Fig. 3c). At EBC, where the glacier debris-cover is thinner, this was –31.3 m, or –1.01 m/yr (Fig. 3d). This lowering equates to a total ice volume loss of –197 649 227 m^3 across the debris-covered area (Fig. 3b). Although Khumbu and other glaciers in the region still act as reservoirs, storing a large amount of water as glacial ice, it is clear that this resource is rapidly depleting, which will affect the magnitude and seasonality of river flows.

Several studies have predicted that a glacial lake will develop on the Khumbu Glacier as mass loss continues, which will itself change the glacier's dynamics. Imja Tsho is a well-known glacial lake, which is expanding by 26 000 m^2/yr. Here, lake water acts to thermally erode the glacier terminus and promote calving into the lake, causing rapid lake expansion and glacial retreat. In addition to

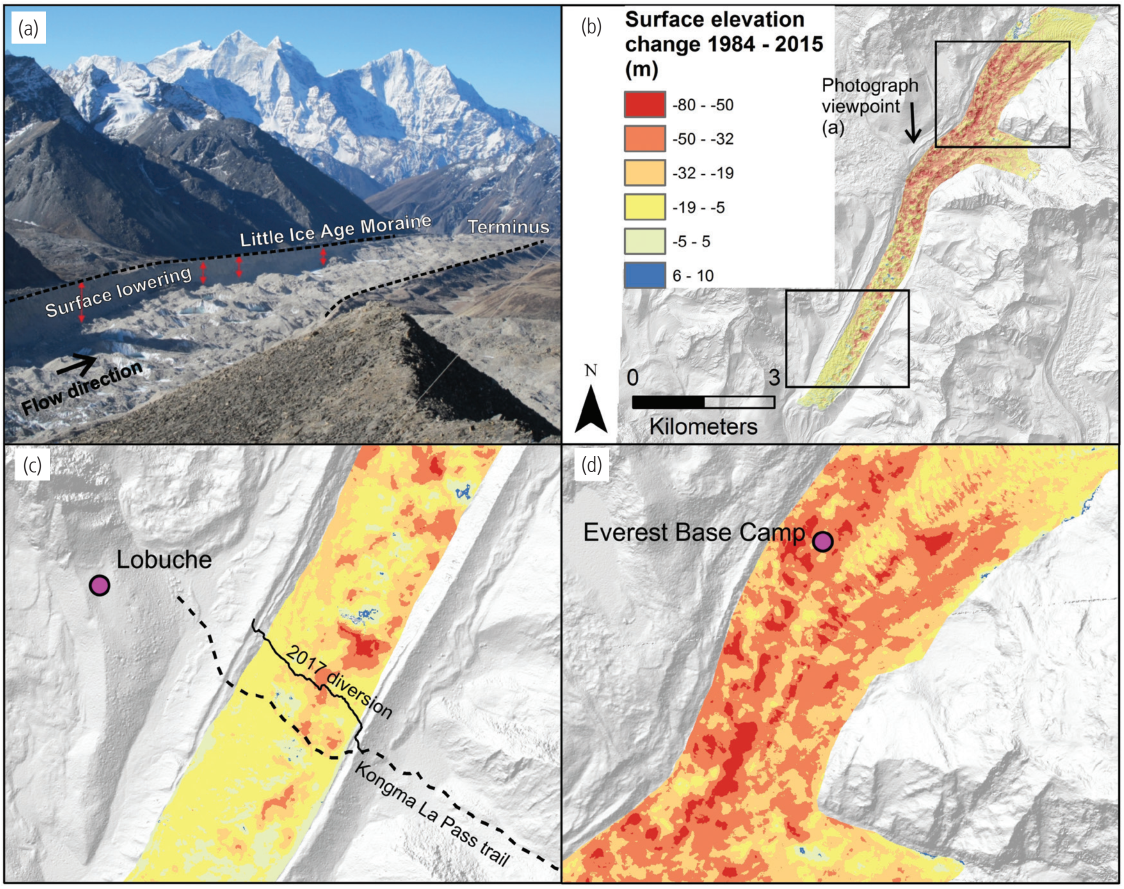

Fig. 3. a. The lower debris-covered tongue of Khumbu Glacier showing the contemporary glacier surface in relation to the Little Ice Age moraines. **b.** Surface elevation change on Khumbu Glacier 1984–2015 with a hillshaded DEM backdrop. Inset locations are: **c.** Lobuche and **d.** Everest Base Camp.

acting as a positive-feedback mechanism promoting glacier mass loss, glacial lakes require assessment and monitoring strategies to address their outburst flood risk, and in extreme cases, remediation to mitigate against potential flooding.

Glacier velocity

Variations in glacier thickness and the surface gradient of a glacier control the driving stress required for glacier movement. Driving stress decreases as glaciers thin, since melting ice in the ablation zone is not replaced by sufficient ice flux generated from snowfall in the accumulation zone. Therefore, glacier velocity is expected to decrease in response to reduced snow accumulation at high elevations and ongoing surface lowering at lower elevations.

We used the feature tracking algorithm in COSI-Corr (an add-on for the remote sensing package, ENVI) to derive glacier velocities using two Planet Labs satellite images acquired in 2016 and 2017. The stagnant tongues of Khumbu and Ngozumpa glaciers are visible in Fig. 4, where flow velocity reduces from rates exceeding 50 m/yr to less than 10 m/yr several kilometres up-glacier from respective termini. The englacial drainage system is subject to less disturbance where glacier velocities are low, hence supraglacial ponds are less likely to drain into the glacier through fractures at the pond bed. Therefore, as relic conduits collapse to produce new surface depressions and the glacier becomes thinner, the conditions become favourable for larger glacial lakes to form near the glacier terminus as individual ponds coalesce (e.g. Fig. 5).

Glacier accessibility

Glacier surface lowering and velocity influence the accessibility of the surface, which is a function of its topographic characteristics, including slope and surface roughness; and surface features, including supraglacial ponds, ice cliffs, debris-cover and crevasses. Topographic characteristics can be modelled using a DEM and geographical information system software to characterize the difficulty or ‘cost’ encountered by a person crossing the glacier surface (Fig. 5). Here terrain difficulty was calculated using surface slope averaged over a 10 × 10 m moving window, and surface roughness, which we approximate using the standard deviation of elevation over a 10 × 10 m moving window. Impassable features were incorporated into the terrain difficulty layer and included supraglacial ponds, and slopes with angles greater than 35°. Least-cost paths were then

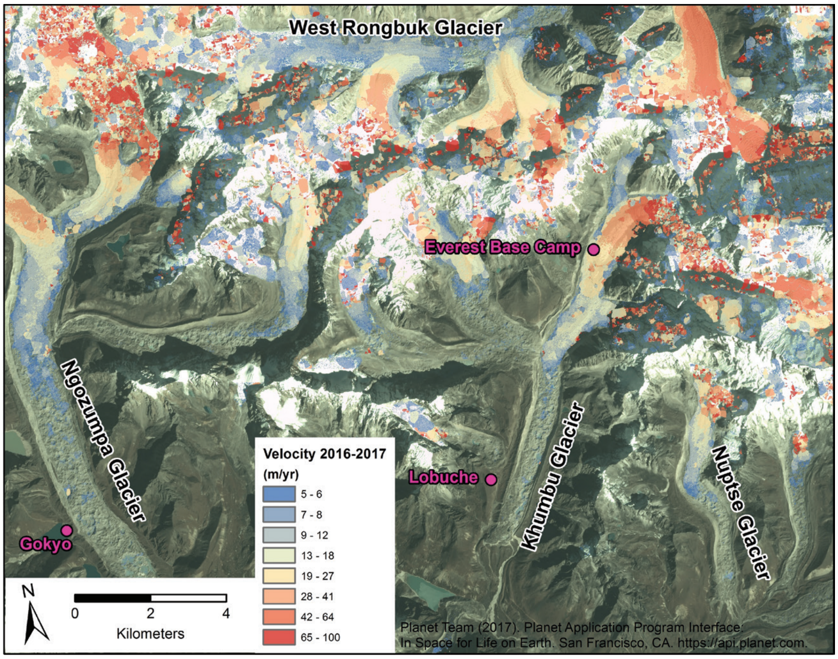

Fig. 4. Glacier velocities (2016–2017) derived from feature tracking on PlanetScope satellite imagery.

calculated across the glacier at the location of the Kongma La Pass trail using 50 randomly generated start and end locations (Fig. 5).

Accessibility across the Khumbu Glacier decreased from 1984 to 2015, shown by the reduction from five main paths crossing the glacier to three respectively. This is largely due to the expansion of supraglacial ponds, which increased in area from 28 755 m^2 to 139 015 m^2 (383%) from 1984 to 2015 in the location shown (Fig. 5). The three remaining crossing points exploit the last remaining land bridges between the connected chains of ponds. Without these land bridges the Kongma La Pass trail would require a detour around the front of the glacier and based on pond expansion rates from 2011 to 2015, these land bridges are likely to disappear by 2020. The cost of crossing the glacier surface is also affected by the surface lowering such that accessing the glacier surface requires a greater and in some cases steeper descent, followed by a greater ascent off the glacier. The average cost of crossing Khumbu Glacier considering all routes increased by 19% from 1984 to 2015 (Fig. 5). Notably, the trail changed in 2017 due to the loss of one land bridge, and the opening of a new crossing point due to the partial drainage of a supraglacial pond.

We also performed the least-cost path analysis on Ngozumpa Glacier at the location of the Chola Pass trail. There are no clear pinch-points where the route is likely to become blocked within the next five years and although the route will likely change in response to supraglacial pond expansion and ice cliff retreat, there are still many opportunities for small diversions. However, up-glacier expansion of Spillway Lake on the terminus of the glacier may ultimately prevent across-glacier access since estimates suggest it could become several kilometres long.

Collaborative science in the high-mountain environment

Environmental scientists have access to a range of datasets, which can be used to monitor glacier surface elevation change, glacier velocity, supraglacial pond dynamics and land cover change. However, field campaigns are generally restricted to elevations < 6000 m, which means there are limited measurements of high-altitude glacier characteristics and snow accumulation. Precipitation rates are essential inputs to models of future glacier mass balance and could be better understood through the collection of snow cores in glacier accumulation zones. Sherpas and mountaineers who routinely access the high-mountain environment have an understanding of local environmental changes and have the logistical infrastructure that could be used

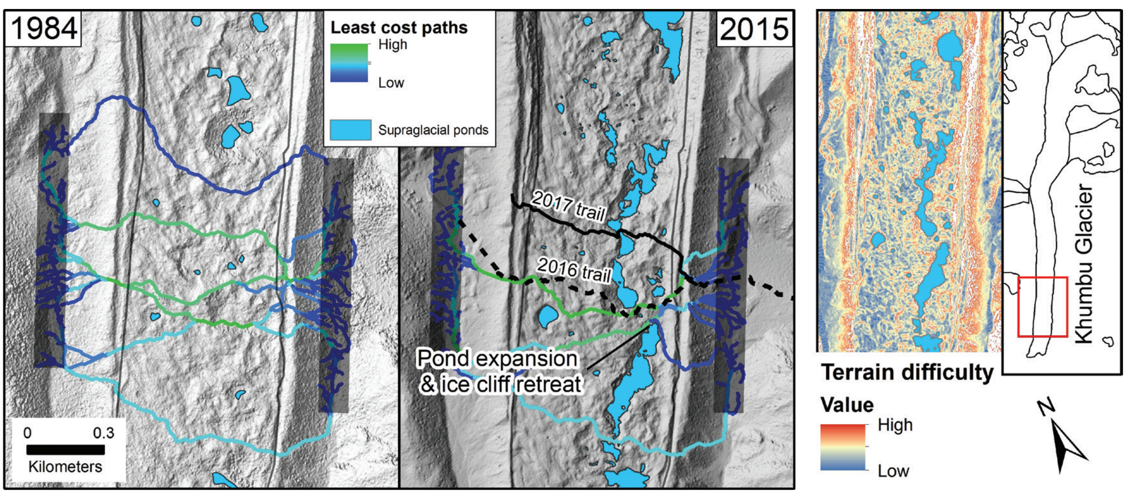

Fig. 5. A least-cost path (LCP) assessment of accessibility across the Khumbu Glacier using DEMs from 1984 and 2015. Hillshaded DEMs are used as the backdrop. A high number of least cost paths indicates an easier crossing route. The LCPs are derived by considering terrain difficulty and the presence of barrier features such as ice cliffs, supraglacial ponds and steep slopes.

Table 1. Collaborative opportunities to improve climate change adaptation in the high-mountain environment

	Knowledge base and collaborative opportunities	Benefits
Local communities	Observations of environmental change e.g. snow cover, precipitation seasonality, growing season, flood events	Used to complement remote sensing change detection and forecast future change
	Participatory science e.g. collecting repeat photographs and water samples	Documentation of landscape change. Measuring river flow contributions from glacier melt, snow melt, and rainfall, which can be used to guide water use and storage strategies
	Links with mountaineering Sherpas and village development committees	Dissemination and discussion of scientific findings and adaptation strategies
Local and international mountaineers	Regular visits to the high-mountain environment over decadal timescales	Multi-temporal photograph archives documenting snow/ice cover change Specialist knowledge of the high-mountain environment
	Logistical support and permits. Mountaineers becoming partners on scientific grants	Access to high altitude peaks where scientific equipment could be transported and snow samples retrieved. Public exposure of scientific activities and mountaineering partners
	GPS track-logs	Documentation of route choice. Multi-temporal measurements of route elevation.
Scientific community	Interpretation of satellite imagery archives and access to fine-resolution imagery and digital elevation models	Mountaineering route selection and hazard identification Flood modelling to identify glacial lake outburst flood risk
	Long-term temperature, precipitation and river flow data	Forecasting hydrological change due to climatic warming

to transport scientific equipment and samples. The expert views of local and international mountaineers are therefore valuable to the scientific community, and collaborations could have mutual benefits for monitoring and forecasting changes in the high-mountain environment (Table 1).

We sought the views of three Mount Everest mountaineers regarding environmental change, and opportunities for scientific collaboration, which are summarized in Fig. 6. Several key themes emerged including an increased frequency of rockfall events requiring climbing route changes, and reduced snowfall and changing weather patterns creating harder climbing conditions. Warming temperatures are known to affect the stability of mountain rock slopes, such that the loss of snow cover and glacial debuttressing are likely accompanied by an increase in rockfall activity. Additionally, temporal changes in the summer monsoon and declining precipitation trends are observed around Everest, which were also identified by the mountaineers. It was suggested that climbing conditions would become more difficult if these trends continue and there would be a shift in preferable locations and routes for mountaineering activities.

Opportunities for collaborations included the communication of important trends to the mountaineering community in an easily accessible form (e.g. dated maps), and collaborative expeditions where scientists or scientific equipment could 'piggyback' on mountaineering expeditions. In lower altitude mountainous regions (e.g. the European Alps), there is less distinction between scientific and mountaineering communities and indeed many glaciologists would also identify as mountaineers. However, in the high-altitude Himalaya, expeditions typically require more extensive logistical and technical support and the acquisition of mountaineering permits, which restricts scientific access. Cooperation with local and international expeditions could therefore be highly beneficial to both parties, since the derived scientific work would be directly relevant to supporting expeditions.

Summary

Himalayan glacier mass loss will continue in response to climatic warming, which will influence river flows, the development of glacial lakes, and access to the high-mountain environment. Reduced glacier and mountain accessibility has implications for mountaineers and trekking tourists, which now support entire communities in popular trekking areas. We have presented a case-study from the Sagarmatha

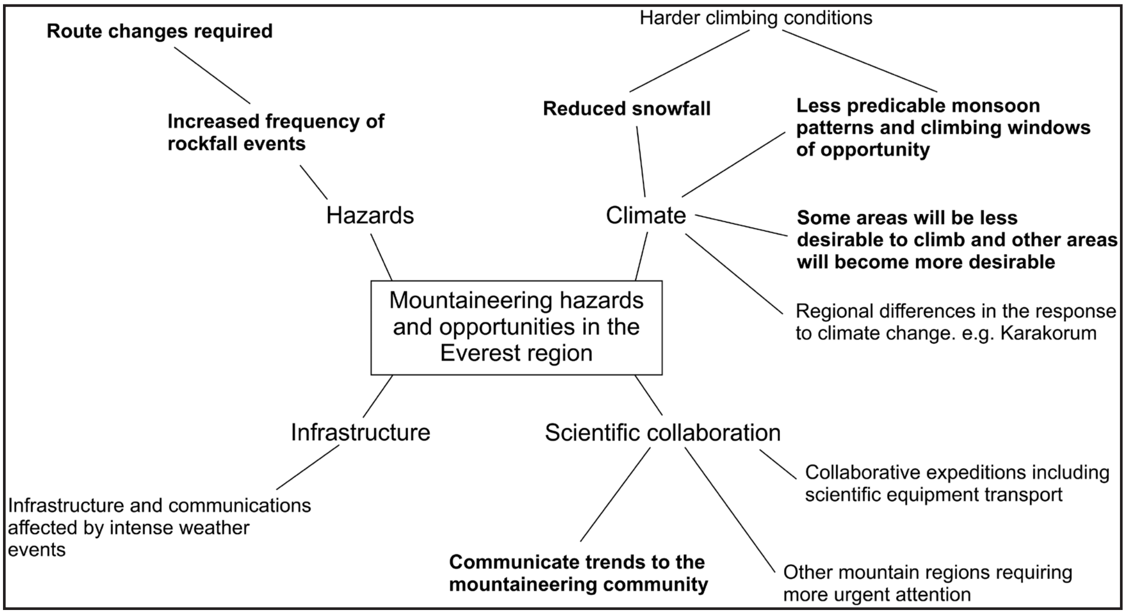

Fig. 6. A summary of mountaineering hazards and opportunities in the Everest region identified by mountaineers. Bold text indicates themes identified by several mountaineers.

National Park in Nepal where glacier mass loss is affecting trekking and mountaineering activities around the world's highest peak. We revealed that ongoing expansion of supraglacial ponds on the Khumbu Glacier is likely to block the Kongma La Pass trail by 2020, which will require diversion around the glacier terminus. In contrast, the Chola Pass trail on Ngozumpa Glacier has alternative pathways available to avoid expanding ponds and ice cliffs, although this may change in coming decades if Spillway Lake continues to expand up-glacier.

Additionally, expert opinion from Everest mountaineers suggest that rockfall events and changing weather patterns will increasingly affect mountaineering activities as the climate warms and snowfall decreases in the region. We propose that collaboration between scientists and mountaineering expeditions offer a valuable opportunity for data collection, and direct feedback of these results could be used to inform expedition planning.

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Suggestions for further reading

Bolch, T., Pieczonka, T. & Benn, D.I. 2011. Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery. *The Cryosphere*, v.5, pp.349–358.

Carrivick, J.L. & Tweed, F.S. 2016. A global assessment of the societal impacts of glacier outburst floods. *Global and Planetary Change*, v.144, pp.1–16.

Garrard, R., Kohler, T., Price, M.F., Byers, A.C., Sherpa, A.R. & Maharjan, G.R. 2016. Land use and land cover change in Sagarmatha National Park, a World Heritage Site in the Himalayas of eastern Nepal. *Mountain Research and Development*, v.36, pp.299310.

King, O., Quincey, D.J., Carrivick, J.L. & Rowan, A.V. 2017. Spatial variability in mass loss of glaciers in the Everest region, central Himalayas, between 2000 and 2015. *The Cryosphere.* v.11, pp.407–426.

Leprince, S., Barbot, S., Ayoub, F. & Avouac, J.P. 2007. Automatic and precise orthorectification, coregistration, and subpixel correlation of satellite images, application to ground deformation measurements. *IEEE Transactions on Geoscience and Remote Sensing*, v.45, pp.1529–1558.

McColl, S.T. 2012. Paraglacial rock-slope stability. *Geomorphology*, v.153–154, pp.1–16.

Miles, E.S., Pellicciotti, F., Willis, I.C., Steiner, J.F., Buri,

P. & Arnold, N.S. 2016. Refined energy-balance modelling of a supraglacial pond, Langtang Khola, Nepal. *Annals of Glaciology*, v.57, pp.29–40.

Nuimura, T., Fujita, K., Yamaguchi, S. & Sharma, R.R. 2012. Elevation changes of glaciers revealed by multitemporal digital elevation models calibrated by GPS survey in the Khumbu region, Nepal Himalaya, 1992-2008. *Journal of Glaciology*, v.58, pp.648–656.

Planet Team. 2017. Planet application program interface. In: *Space for Life on Earth*. San Francisco, CA. https://api.planet.com.

Quincey, D.J., Luckman, A. & Benn, D. 2009. Quantification of Everest region glacier velocities between 1992 and 2002, using satellite radar interferometry and feature tracking. *Journal of Glaciology*, v.55, pp.596–606.

Rounce, D.R., Byers, A.C., Byers, E.A. & McKinney, D.C. 2017. Brief communication: observations of a glacier outburst flood from Lhotse Glacier, Everest area, Nepal. *The Cryosphere*, v.11, pp.443–449.

Rounce, D.R., McKinney, D.C., Lala, J.M., Byers, A.C. & Watson, C.S. 2016. A new remote hazard and risk assessment framework for glacial lakes in the Nepal Himalaya. *Hydrology and Earth System Sciences*, v.20, pp.3455–3475.

Rowan, A.V., Egholm, D.L., Quincey, D.J. & Glasser, N.F. 2015. Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya. *Earth and Planetary Science Letters*, v.430, pp.427–438.

Sakai, A., Takeuchi, N., Fujita, K. & Nakawo, M. 2000. Role of supraglacial ponds in the ablation process of a debris-covered glacier in the Nepal Himalayas. In: Nakawo, M., Raymond, C.F. & Fountain, A., eds. *IAHS Publ. 264 (Symposium at Seattle 2000—Debris-Covered Glaciers)*, *Seattle, WA, USA*. IAHS Publishing, pp.119–130.

Salerno, F., Guyennon, N., Thakuri, S., Viviano, G., Romano, E., Vuillermoz, E. Cristofanelli, P., Stocchi, P., Agrillo, G., Ma, Y. & Tartari, G. 2015. Weak precipitation, warm winters and springs impact glaciers of south slopes of Mt Everest (central Himalaya) in the last 2 decades (1994–2013). *The Cryosphere*, v.9, pp.1229–1247.

Shea, J.M., Immerzeel, W.W., Wagnon, P., Vincent, C. & Bajracharya, S. 2015. Modelling glacier change in the Everest region, Nepal Himalaya. *The Cryosphere*, v.9, pp.1105–1128.

Thakuri, S., Salerno, F., Bolch, T., Guyennon, N. & Tartari, G. 2016. Factors controlling the accelerated expansion of Imja Lake, Mount Everest region, Nepal. *Annals of Glaciology*, v.57, pp.245–257.

Thompson, S., Benn, D., Mertes, J. & Luckman, A. 2016. Stagnation and mass loss on a Himalayan debris-covered glacier: processes, patterns and rates. *Journal of Glaciology*, v.62, pp.467–485.

Watson, C.S., Quincey, D.J., Carrivick, J.L. & Smith, M.W. 2016. The dynamics of supraglacial ponds in the Everest region, central Himalaya. *Global and Planetary Change*, v.142, pp.14–27.

Watson, C.S., Quincey, D.J., Carrivick, J.L. & Smith, M.W. 2017. Ice cliff dynamics in the Everest region of the Central Himalaya. *Geomorphology*, v.278, pp.238–251.