One Earth

Primer

An Overview of Physical Risks in the Mt. Everest Region

Kimberley R. Miner,[1,*] Paul A. Mayewski,[1] Saraju K. Baidya,[10] Kenneth Broad,[9,11,13] Heather Clifford,[1,8] Aurora Elmore,[9] Ananta P. Gajurel,[3] Bibek Giri,[2] Sam Guilford,[9] Mary Hubbard,[2] Corey Jaskolski,[13] Heather Koldewey,[7] Wei Li,[12] Tom Matthews,[4] Imogen Napper,[6] L. Baker Perry,[5] Mariusz Potocki,[1,8] John C. Priscu,[12] Alex Tait,[9] Richard Thompson,[6] and Subash Tuladhar[10]
[1]Climate Change Institute, University of Maine, Orono, ME, USA
[2]Department of Earth Sciences, Montana State University, Bozeman, MT, USA
[3]Department of Geology, Tribhuvan University, Kathmandu, Nepal
[4]Department of Geography and Environment, Loughborough University, Loughborough, UK
[5]Department of Geography and Planning, Appalachian State University, Boone, NC, USA
[6]International Marine Litter Research Unit, University of Plymouth, Plymouth, UK
[7]Zoological Society of London, London, UK
[8]School of Earth and Climate Sciences, University of Maine, Orono, ME, USA
[9]National Geographic Society, Washington DC, USA
[10]Department of Hydrology and Meteorology, Kathmandu, Nepal
[11]Abess Center for Ecosystem Science, University of Miami, Miami, FL, USA
[12]Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT, USA
[13]Virtual Wonders, LLC, Delafield, WI, USA
*Correspondence: kimberley.miner@maine.edu
https://doi.org/10.1016/j.oneear.2020.10.008

SUMMARY

In April and May 2019, as part of National Geographic and Rolex's Perpetual Planet Everest Expedition, an interdisciplinary scientific effort conducted a suite of research on the mountain and recognized many changing dynamics, including emergent risks resulting from natural and anthropogenic changes to the biological system. In this Primer, the diverse research teams highlight risks to ecosystem and human health, geologic hazards, and changing climbing conditions that could affect the local community, climbers, and trekkers in the future. We bring together perspectives from across the atmospheric, biological, geological, and health sciences to highlight the need to better understand emergent risks on Mt. Everest and in the Khumbu region. Understanding these risks is critical for the ~10,000 people living in the Khumbu region, the thousands of visiting trekkers, and the hundreds of climbers who attempt to summit each year.

INTRODUCTION

Mountain systems are changing rapidly throughout the world in response to climate change and human impacts. Loss of water stored in glacial reservoirs, precipitation changes, and warming at high altitudes affect alpine ecosystems globally. High mountain glaciers worldwide are decreasing in extent and volume at dramatic rates with significant consequences for water availability, hazards (such as glacier lake outburst floods and slope failure), ecosystems, and socioeconomic futures. Climatic changes in the Hindu Kush-Himalaya are of particular concern given the region's 250 million Nepali, Tibetan, and Chinese inhabitants, rich biodiversity, and some 2 billion more lives downstream who depend on the mountains' bounty for water and food, among other services. With environmental changes occurring rapidly, it is critical that we elucidate potential risks for all people and ecosystems in the Himalayas. Driven by climate change dynamics, known physical threats such as landslides, avalanches, and blizzards are compounded by hazards such as the introduction of pollutants. These threats can potentially affect a variety of environmental services critical to the stability of the below-glacier population. For example, both outburst flooding and the corollary or glacier wastage can affect water and water infrastructure availability and resilience. Landslides, avalanches, and blizzards present challenges to the physical safety of residents and supporting infrastructure. Polluted meltwater can limit the available water for use in agriculture and by the resident populations (Figure 1).

At the confluence of these hazards, Mt. Everest and the Khumbu watershed present unique challenges from a significant inflow of tourists, trekkers, and local visitors. As one of the most climbed mountains globally, the health, safety, and livelihoods of residents and visitors alike are tied to this unique mountain system's stability. Therefore, to illustrate first-order risks with the potential to increase under a warming climate, we present a primer to introduce the Mt. Everest region's hazards, where the ~10,000 residents and thousands of annual tourists, trekkers, and climbers witness and experience these changes first hand.

Geologic Risks

The Khumbu region of Nepal, including Sagarmatha National Park, is host to several geologic hazards. This mountain region contains the highest elevation globally and balances tectonic

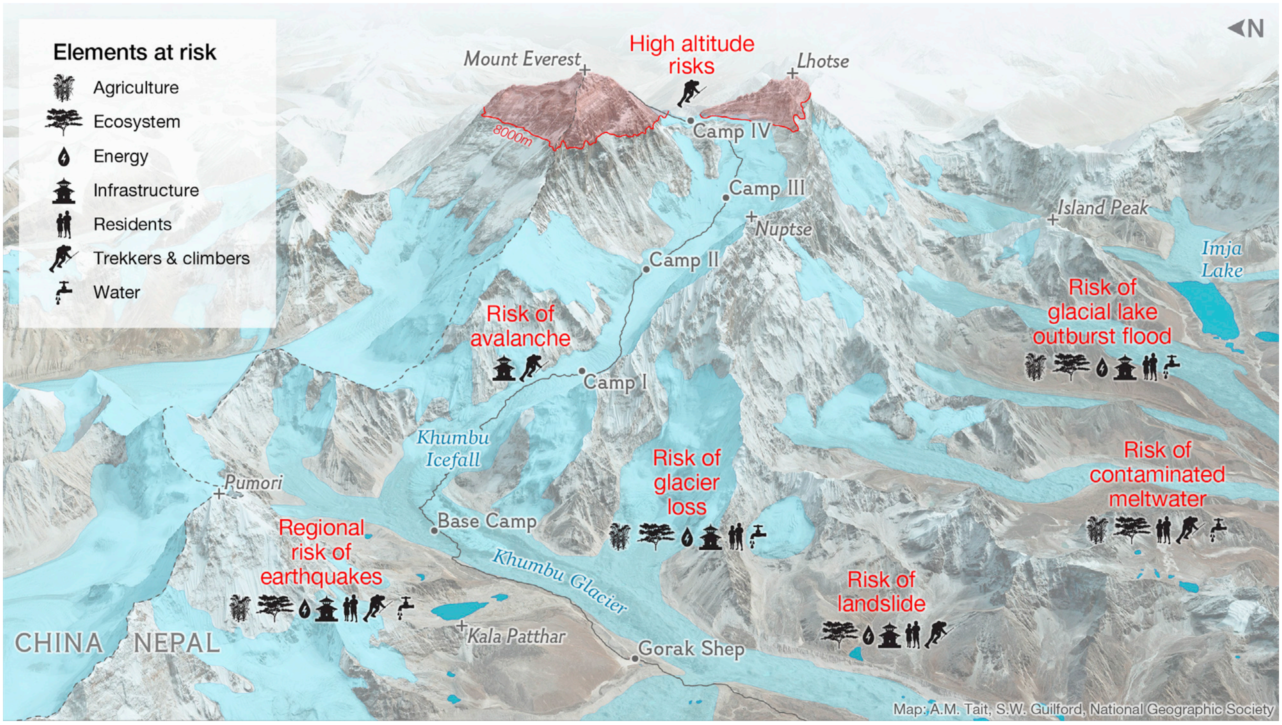

Figure 1. A High-Level Overview of Some of the Physical Risks and Secondary Impacts within the Mt. Everest Watershed

uplift with erosional processes. The result is a network of steep glacial headwalls with active erosion and stream incision. The seismic hazard is ever-present throughout the Himalayas and heightens the risk of mass movements and avalanches that can threaten the lives and livelihoods of residents and visitors alike.

The high elevation mountains and topographic relief in the Himalayas represent crustal deformation and erosional processes dissecting the Earth's crust in this region. As India continues its generally northward movement, this interplay of processes shapes the mountain belt and can increase the risk of landslides and earthquakes on a yearly timescale. In the Himalayas, hillslopes tend to be steep and erosion rates are high, calibrated by the strength of the rock and soil, topography, vegetation, and climatic conditions. The steep hillslopes are susceptible to hazardous erosion, landslides, and avalanches and present a risk for people and property in the Khumbu region. The highest-risk areas are often concentrated along the river valleys or steep valley walls, which host most of the settlements in the Mt. Everest watershed, enhancing the potential for impacts to infrastructure, agriculture, and the lives of residents (Figure 1).

Glacial and fluvial erosion from the last ice age to today also shapes the Khumbu region. There is a diversity of landslide scarps and deposits, such as the village of Namche Bazar (below Mt. Everest), built in the bowl-shaped scarp from a past landslide. That scarp cuts into an earlier massive rockslide, the Khumjung slide, which is currently the sixth-largest rockslide documented in Nepal. Though now stable, this human adaptation to a changing environment highlights the ongoing threat to infrastructure and ecosystem stability presented by unstable morphology. Rockslides of this magnitude account for a large percentage of the erosion across the high-relief Himalaya. Although high-magnitude slides occur infrequently, they may be triggered by earthquake events or glacial flow dynamics. High-volume high-velocity landslides, including rockfalls, rockslides, and debris flows, pose a geologic hazard to people and infrastructure throughout the Khumbu region (Figure 1). Indeed, it has been documented that earthquakes often trigger landslides and avalanches of all sizes.

As climate changes and glaciers retreat, they melt away from the headwalls, exposing steep rock faces that increase their vulnerability to failure. All landslides, including those triggered by earthquakes and glacier recession, can introduce cascading hazards, including the flooding of river valleys, rockslides, and avalanches. These geologic events can significantly harm residents, agriculture, ecosystem health, and infrastructure, causing damage and loss of life (Figure 1). Understanding the glacial and geomorphological changes is critical to protecting both the local inhabitants of the Khumbu region and its visitors.

Rocks of the Khumbu region have been subjected to deformational processes for the past ~55 million years, creating regular failure planes. These planes can be due to a weaker lithology or prior faulting or shearing of the bedrock. Once the incision of streams and glaciers steepens hillslopes, these weak planes are vulnerable to failure. Active faults at depth exacerbate landslide risk through earthquake occurrence. Following the 2015 Gorkha earthquake in Nepal, a debris avalanche consisting of ice, snow, and rock material buried the Langtang village, killing over 200 people. The quake caused similar massive snow and ice avalanche at Base Camp, a dynamic that could be repeated with the often multi-decadal earthquake occurrence. There are too many variables in our Earth's crust to predict earthquakes precisely. Nevertheless, seismologists have done significant work studying past earthquakes and rates of modern tectonic plate movement. This research allows scientists to understand areas along the Himalayas at higher risk of earthquakes, but more work to constrain the risks and impacts is needed.

Hydrological Risks

Throughout the Khumbu, rain events have triggered dangerous flooding and landslides. The likelihood of these hazards may increase in the region, consistent with projections of upward trends in precipitation events across South Asia. These changes suggest a rising probability of heavy rain (as opposed to snow) falling in glacierized basins, leading to increased flood risk. These risks increase when glacial melt and rain events combine.

Glacial lake outburst floods are directly tied to the evolving geomorphology of a warming climate. The increasing loss of glacial stability presents almost yearly opportunities for these events to occur. Outburst floods occur as glaciers retreat and leave newly formed lakes impounded by their former moraine walls. These lakes are at risk of a catastrophic breakthrough in this impoundment and subsequent flooding. Outburst floods of glacial lakes are most often triggered by mass movements into the lakes, including avalanches, landslides, or rockfall (Figure 1). As glacial melt accelerates, the formation of supraglacial lakes on the glacier surface becomes a yearly hazard as these lakes are isolated from meltwater release points. If supraglacial lakes suddenly break their banks, they can release significant water flow and downstream flooding.

To assess the risk posed by outburst floods, detailed digital elevation data are used to map glacier surfaces to increase scientists' understanding of terminal and supraglacial lakes. Given that there has been a history of outburst floods in the Khumbu, the lakes are monitored, and engineering modifications (the lowering of Imja Lake, for example) may reduce the risk.

However, the corollary risk is also present. With more significant glacier retreat, average river flows may decline in the latter half of the century. Subsequent water stress in the Everest region could become frequent, with a reduction in glacier meltwater buffering against seasonal meteorological drought. In turn, this could decrease local communities' food and economic security.

High-Altitude Risks

Climbers who venture to Everest's upper slopes may be in danger of acute mountain sickness triggered by hypoxia caused by the low barometric air pressure. Other atmospheric hazards are also possible. For example, the risk from the extreme cold may be severe, with frostbite possible in under one minute when low temperatures coincide with strong winds. Heavy snowfall increases the avalanche threat and slows progress at high elevations, magnifying the risk from cold and acute mountain sickness. The nearly 800 people per year attempting to summit Mt. Everest would be most at risk from the most significant high-altitude hazards at altitudes up to 8,000 m.

Inhaled ozone can also cause health impacts in otherwise healthy adults climbing to Base Camp or beyond. Research from the Khumbu Valley shows that ozone levels regularly exceed recommended safety limits. This is primarily due to the long-range transport of polluted tropospheric air masses from the Indo-Gangetic Plain and the stratospheric air intrusions. Intermittent measurements from high altitudes on Mt. Everest suggest that ozone levels generally increase with elevation, consistent with an increasing influence of stratospheric air and accelerated phytochemistry from enhanced solar radiation.

The timing and location of these peak ozone concentrations may place mountaineers at significant risk. May is the most popular month for Everest summit attempts but is also the month when ozone safety levels identified by the World Health Organization are frequently breached. Climbers attempting to summit Everest may often encounter ozone concentrations at levels associated with measurable reductions to lung function in the short term or significant health impacts in the long term. Risks from high-altitude exposure predominantly affect the climbers and Sherpas trying to summit Mt. Everest. However, air-quality forecasts near the summit could be developed to mediate risk, particularly for those attempting to climb without supplementary oxygen. Although all climbers may be exposed to high-altitude threats, Sherpas may make multiple trips per year and may see increased opportunities for each trip's adverse effects (Figure 1).

Water Pollution Risks

Throughout the world, centuries-old ice stored in glaciers is melting to reveal the footprint of human chemical use. Studies throughout Europe, Asia, and North America have identified chemicals as diverse as pesticides, industrial plasticizers, and lead in snow and glacier ice. The melting of this ice has led to water contamination by anthropogenic sources in some of the world's most important water towers. With the expansion of tourism and infrastructure development, local emissions and long-range transport could increase chemical concentrations in surface snow and glacier melt streams in the Khumbu region.

Asia is the most significant global contributor of anthropogenic metals to the atmosphere due to increased industrial production and the general lack of emission controls. Metal contamination can be deposited in watersheds atmospherically and subsequently emerge in water used for drinking, irrigation, and ecological purposes. These deposited metals can create health problems if they exceed safety levels.

Ten years after the first successful climb of Mt. Everest, it was described as "the world's highest junkyard." Given the fragile environment, extreme weather conditions, and limited infrastructure, the waste produced is often beyond local capacity to handle, increasing local towns' and economies' stress. Plastic pollution is a more recent challenge to local populations unable to manage the challenges associated with generations of trekkers.

The inflow of climbers also brings the potential for enhanced release of ice-entombed pathogenic organisms. The release of pathogenic bacteria in glacial transport of fecal bacteria from climbing activities may cause health problems for local populations. Reports of buried human waste from climbers at the glacier surface directly result from rapid glacier melt. However, positive actions have recently been invoked to address the risks of pollution on the mountain. For example, in February 2019, China closed its Everest base camp on the Qinghai-Tibetan Plateau due to waste accumulation. The government also banned single-use plastics starting January 2020 in a bid to cut down on waste left by climbers. Anthropogenic waste and chemical pollution can pose significant risks to the health of residents.

The risk from compounds in meltwater increases with the amount of exposure time. Therefore, it is likely that the risks to residents are higher than to any visitors to the area. Threats from the uptake of water pollution may be greater than the risk from pollutant infiltration in agriculture. However, the combination of decreasing water quality and quantity may prove a significant challenge for people, plants, and animals alike (Figure 1).

An immediate step to reduce the risk of exposure for the local population is to integrate filters to remove heavy metals in streams and snowmelt before drinking. Long-term management could include increased water testing throughout the below-glacier watershed and expanding local regulations on tourism, pollution control, and waste removal. In future research, sampling for toxic chemicals, plastics, and metals must be prioritized across the Khumbu region's landscape to protect trekkers' and residents' health.

CONCLUSION

As the highest mountain in the world, Mt. Everest is considered one of the most coveted climbs for mountaineers across the globe. However, the risks to visitors and residents' health and safety multiply as climate change and increased traffic change the mountain's dynamics. Residents living in the Khumbu watershed may experience the impacts of physical hazards and anthropogenic contamination more directly than visitors, increasing their risk to long-term health and safety. For these residents, tourism brings both revenue and health risk to the region. As the changing climate produces increasingly dynamic conditions, these risks may present a growing burden to the local population.

The ecosystem changes driven by climate warming expose hidden effects on humans across landscapes, where our influences are seen even on the highest mountain on Earth. This frozen chemical signature of human interaction is an unfortunate side effect of innovation that becomes increasingly harmful as glaciers melt at an unprecedented rate. In the future, it will be necessary to expand our understanding of the diversity of risks posed by the mountain and to monitor the status of these changing conditions. Assembling teams of interdisciplinary researchers to document and understand the dynamic environment of Mt. Everest is a significant step toward protecting this resource for generations. Understanding ice dynamics, geology, and precipitation dynamics are critical to adapting to both the local community and the mountaineering teams. While not all of the mountaineers from Mt. Everest are from the Khumbu region, their actions on the mountain may affect the local community past their departure. Thoughtful discussion of the risks that tourism and climate change bring to the Khumbu watershed community, and the surrounding Himalayas, is essential to provide a clear picture of a sustainable future.

AUTHOR CONTRIBUTIONS

All authors contributed to developing and producing the content of the manuscript. K.R.M. contributed by editing and coordinating the production of the manuscript. P.A.M., H.C., and M.P. wrote and edited the section on pollution contamination in snow and ice. I.N., R.T., and H.K. wrote and edited the section on water pollution and microplastics. M.H., G.B., and A.P.G. wrote and edited the section on physical risks including landslides and glacial lake outburst flooding. J.C.P. and W.L. wrote and edited the section on parasite risk and water risk. T.M. and L.B.P. wrote and edited the section on high-altitude risks and precipitation changes. K.B. and C.J. created figures for reference and assisted with the Introduction and Summary sections. S.T., S.K.B., and A.E. edited the manuscript for accuracy and specificity. S.G. and A.T. created and edited the figure of Mt. Everest and the corresponding description.

RECOMMENDED READING

Bilham, R. (2019). Himalayan earthquakes: a review of historical seismicity and early 21st-century slip potential. In Himalayan Tectonics: A Modern Synthesis, *483*, P.J. Treloar and M.P. Searle, eds. (The Geological Society), pp. 423–482.

Byers, A.C., Rounce, D.R., Shugar, D.H., Lala, J.M., Byers, E.A., and Regmi, D. (2019). A rockfall-induced glacial lake outburst flood, Upper Barun Valley, Nepal. Landslides *15*, 533–549.

Fort, M., Smadja, J., Khanal, N.R., and Shrestha, B.R. (2019). Landslides and other damage to buildings and infrastructures following the April-May 2015 earthquake sequence, Solukhumbu District, Eastern Nepal. J. Nepal Geol. Soc. *59*, 95–106.

Panday, P.K., Thibeault, J., and Frey, K.E. (2015). Changing temperature and precipitation extremes in the Hindu Kush-Himalayan region: an analysis of CMIP3 and CMIP5 simulations and projections. Int. J. Climatol. *35*, 3058–3077.

Pritchard, H.D. (2019). Asia's shrinking glaciers protect large populations from drought stress. Nature *569*, 649–654.

Gentle, P., and Maraseni, T.N. (2012). Climate change, poverty, and livelihoods: adaptation practices by rural mountain communities in Nepal. Environ. Sci. Pol. *21*, 24–34.

Miner, K.R., Kreutz, K.J., Jain, S., Campbell, S., and Liljedahl, A. (2019). A screening-level approach to quantifying risk from the glacial release of organochlorine pollutants in the Alaskan Arctic. J. Expo. Sci. Environ. Epidemiol. *29*, 293–301.

Bonasoni, P., Cristofanelli, P., Marinoni, A., Vuillermoz, E., and Adhikary, B. (2012). Atmospheric pollution in the Hindu Kush-Himalaya region. Mt. Res. Dev. *32*, 468–479.

Xu, J., Badola, R., Chettri, N., Chaudhary, R.P., Zomer, R., Pokhrel, B., Hussain, S.A., Pradhan, S., and Pradhan, R. (2019). Sustaining biodiversity and ecosystem services in the Hindu Kush Himalaya. In The Hindu Kush Himalaya Assessment, P. Wester, A. Mishras, A. Mukherji, and A.B. Shrestha, eds. (Springer Nature), pp. 127–165.

Kaspari, S., Mayewski, P.A., Handley, M., Osterberg, E., Kang, S., Sneed, S., Hou, S., and Qin, D. (2009). Recent increases in atmospheric concentrations of Bi, U, Cs, S, and Ca from a 350-year Mount Everest ice core record. J. Geophys. Res. Atmos. *114*, https://doi.org/10.1029/2008JD011088.

Wood, L.R., Neumann, K., Nicholson, K.N., Bird, B.W., Dowling, C.B., Sharma, S., and Wood, L.R. (2020). Melting Himalayan glaciers threaten domestic water resources in the Mount Everest region, Nepal. Front. Earth Sci. https://doi.org/10.3389/feart.2020.00128.

Goodwin, K., Loso, M.G., and Braun, M. (2012). Glacial transport of human waste and survival of fecal bacteria on Mt. McKinley's Kahiltna glacier, Denali National Park, Alaska. Arctic Antarct. Alp. Res. *44*, 432–445.

Maurer, J.M., Schaefer, J.M., Rupper, S., and Corley, A. (2019). Acceleration of ice loss across the Himalayas over the past 40 years. Sci. Adv. *5*, eaav7266.

Pokharel, B., Yang, S.-Y.S., Meyer, J., Marahatta, S., Nepal, B., Chikamoto, Y., and Gillies, R. (2019). The east-west division of changing precipitation in Nepal. Int. J. Climatol. Early View *40*, 3348–3359.

P. Wester, A. Mishra, A. Mukherji, and A.B. Shrestha, eds. (2019). The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People (Springer Nature). https://doi.org/10.1007/978-3-319-92288-1.