1 **Brief Communication: An Ice-Debris Avalanche in the Nupchu Valley, Kanchenjunga Conservation**
2 **Area, Eastern Nepal**

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19

20 **Abstract** Beginning in December 2020, a series of small-to-medium, torrent-like pulses commenced
21 upon a historic debris cone located within the Nupchu valley, Kanchenjunga Conservation Area (KCA),
22 Nepal. Sometime between 16 and 21 August 2022 a comparatively large ice-debris avalanche event
23 occurred, covering an area of 0.6 km^2 with a total estimated volume of order 10^6 m^3. The area of the
24 debris cone left by the August 2022 event increased the historic debris cone area by 0.2 km^2 (total
25 area: 0.6 km^2). Although no human or livestock deaths occurred, the increase in torrent-like pulses of
26 debris upon this historic debris cone since 2020 exemplifies a style of mass movement that may
27 become increasingly common as air temperatures rise in the region. Although the magnitude of this
28 event was small compared to events like the 2021 Chamoli avalanche, the widespread distribution and
29 frequency of comparable events presents a substantial, and potentially increasing, hazard across High
30 Mountain Asia.

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32
33 **1 Introduction**
34
35 Large magnitude but low frequency events in the high mountains can include a variety of familiar and
36 poorly understood cryospheric processes, including glacial lake outburst floods (GLOFs) (Lamsal et al.
37 2014), snow/ice/rock avalanches (Shugar et al. 2021), landslide-induced avalanches and floods (Byers
38 et al. 2019), englacial conduit floods (Rounce et al. 2017), and others (see: Byers et al. 2022). Today,
39 enhanced communications and remote sensing technologies enable rapid identification and location
40 of such events, often within hours of their occurrence. Many, however, remain unreported because of
41 their remoteness, inaccessibility, poor communications, and/or absence of people (see: Byers et al.
42 2020). In this *Brief Communication,* we report on a large ice-debris avalanche that occurred sometime
43 between 16 and 21 August 2022 in the Kanchenjunga Conservation Area (KCA), eastern Nepal. The
44 event is noteworthy not only because of its probable linkages to climate change impacts in the region,
45 but also because local residents were unaware of its occurrence, as were the Government of Nepal
46 and climate change research entities in Kathmandu. Here we briefly document the event and describe
47 its present and future implications for local communities, scientists, and governments.

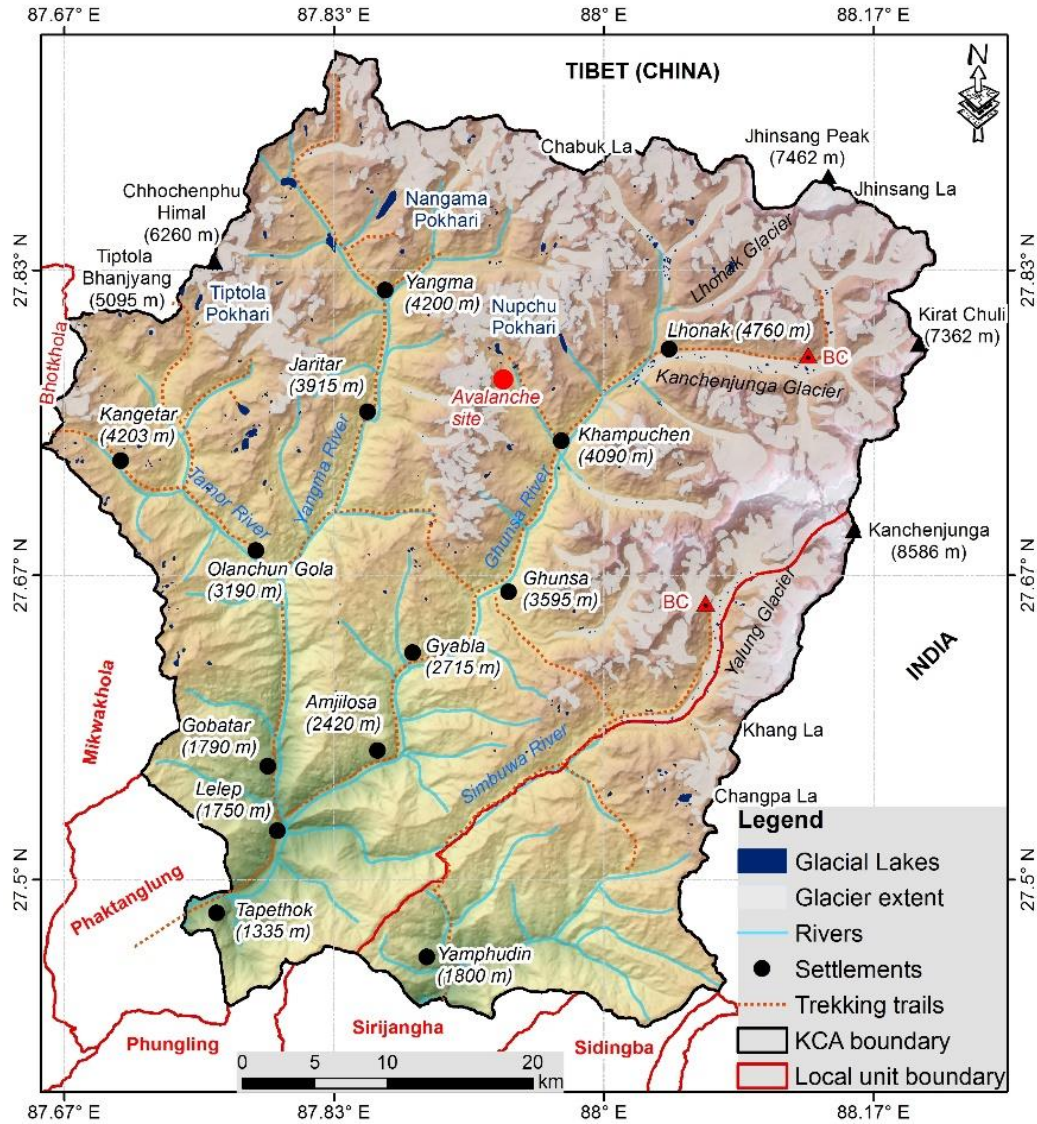



Figure 1. Kanchenjunga Conservation Area and location of the Nupchu ice-debris avalanche.

2 Setting

The KCA is a 2,035 km^2 protected area established in 1997 by the Nepalese Department of National Parks and Wildlife Conservation, with management responsibility handed over to local communities in 2006 (WWF Nepal 2018) (Figure 1). It is home to a range of ethnic groups of primarily Tibeto-Burman origin that include Limbu, Rai, Tamang, Gurung, Magar, Chhetri, and Sherpa (Thapa 2009). Livelihoods were traditionally based upon agriculture, livestock raising, and trade with Tibet, but globalization, outmigration, and new road construction over the past 15 years has rapidly changed the character of both the social and environmental landscape. The South Asian monsoon dominates weather patterns, with most rainfall falling between June and September (Kandel et al. 2019).

Based upon an analysis of 1962–2000 satellite imagery, valley and mountain glaciers in the KCA cover approximately 488 $\pm$ 29 km^2 and exhibit an overall negative glacier surface area loss of 0.5 $\pm$ 0.2% yr^{-1}

65 (Racoviteanu et al. 2015). Valley glaciers are largely debris-covered and have been receding since the
66 most recent maximum during the Little Ice Age. Hooker (1854), for example, wrote in 1849 of
67 observing glacial moraines that provided proof "…of glaciers having once descended to from 8,000 to
68 10,000 feet in every Sikkim and east Nepal valley…" (Hooker 1854: 166). The British alpinist Freshfield
69 (1903: 236) writes of the "glacial shrinkage" he encountered in the Lhonak region in 1899, as well as
70 throughout both the Nepal and Sikkim sides of the Kanchenjunga massif. Although the Kanchenjunga
71 region received some of the earliest study, exploration, and mountaineering expeditions in Nepal by
72 outsiders (Thapa 2009), relatively little glacier and cryospheric hazards research has been conducted
73 to date. For example, until 2019 only one GLOF event was on record for the region (Watanabe et al.
74 1998; ICIMOD 2011), although subsequent research revealed that at least seven others had occurred
75 since 1921 (Byers et al. 2020). The Nupchu valley, where the ice-debris avalanche of concern occurred,
76 is used seasonally for yak herding, potato farming, and tourism, with four operational tourist lodges in
77 the village of Kampuchen as of the fall of 2022 (Figure 1).

78 **3 Methods**
79
80 Field-based observations and assessments of Nupchu Pokhari (glacial lake), other nearby lakes, and
81 the ice-debris avalanche were conducted between 1−20 September 2022. Methods included GPS-
82 based route mapping, photography of avalanche features, oral testimony, and literature reviews.
83 Historic (declassified KH-9 Hexagon satellite imagery; see: Maurer et al. 2019; Dehecq et al. 2020) and
84 recent (Planet Dove and SuperDove) satellite imagery revealed the sequence of avalanche/debris flow
85 events between 1975 and 2023 (Figure 2). Numerical simulations of the avalanche were conducted
86 using R.Avaflow version 3 (Mergili and Pudasaini 2014−2023; Mergili et al. 2017), a state of the art
87 software that has been used globally to study ice/rock avalanches events (Zhang 2022). Numerical
88 simulations were used to provide upper limit volume estimation of the avalanche, which were
89 constrained by field observations. We used the parameters from Zhang et al. (2022) to produce a
90 single-phase model scenario for three different volumes: 1, 2.5, and 5 million m^3. For calibration, we
91 modified the internal friction angle of the mixture to match the extension of the debris left by event.
92 For the terrain elevation, two DEMs were used: the ALOS PALSAR Radiometric Terrain Corrected high
93 resolution 12.5 m DEM (AP_13152_FBD_F0540_RT1) (ASF DAAC 2014) and the High Mountain Asia 8m
94 resolution DEM (Shean, 2017), that was void filled using the Elevation Void Fill function in ArcGIS 10.8.

95 **4 The Event**

96 The investigation of the Nupchu valley was initiated by local concerns about Nupchu Pokhari
97 (27.790708° N, 87.934275° E) as being one of the most dangerous glacial lakes in terms of a potential
98 GLOF (Figure 1). Periodic, smaller floods from the upper Nupchu valley were reported, and assumed
99 locally to have originated in the Nupchu Pokhari, although no supporting evidence was available. Our
100 field reconnaissance results of Nupchu Pokhari on 12 September 2022, however, suggested that the
101 lake posed a moderate risk of flooding, largely based on the absence of overhanging ice and other
102 potential flood triggers. This assessment corroborates the findings of Rounce et al. (2017) which
103 concluded that the 0.129 km^2 Nupchu Pokhari presented only a moderate risk of flooding because of
104 (a) no apparent growth between 2000 and 2015, (b) absence of avalanche pathways into the lake (i.e.,
105 in line with the direction of the lake and its outflow), and (c) absence of landslide pathways entering
106 the lake.

107   The August 2022 ice/debris avalanche event was unexpected. Field staff had conducted a
108   reconnaissance of the valley below Nupchu Pokhari in early August 2022 to check out potential
109   camping sites, at which time the upper valley was primarily pastureland. When the field team and A.C.
110   Byers returned in early September, the original path was blocked by massive ice-debris avalanche
111   material (27.774328° N, 87.941064° E) that had clearly occurred at some point in the interim (Figure
112   2). Our team and *dzopkio* (yak-cattle crossbreeds used as pack animals) were nevertheless able to
113   climb up and over the avalanche debris to the upper Nupchu valley, but at the time the source and
114   triggers related to the event remained unknown.

115   The original historic debris cone was found to have covered an area 0.402 km^2 that had been relatively
116   stable for at least 45 years, based upon the oldest satellite imagery available (i.e., 1975) (Dehecq et al.
117   2020) (Panel A, Figure 2). Time series satellite images revealed the periodic occurrence of surficial
118   debris flows upon this original deposition. That is, beginning in 2020, a series of small-to-medium,
119   torrent-like pulses commenced (Panel C through G, Figure 2), culminating in the relatively large event
120   that occurred sometime between 16 and 21 August 2022 (Panel H, Figure 2). The area of the debris
121   cone left by the August 2022 event increased the original area covered by 0.2 km^2 (total area: 0.6
122   km^2). Of the three different volume estimates tested (1, 2.5, and 5 million m^3) using two DEMs and
123   R.Avaflow, an avalanche volume of 1 x 10^6 m^3 using an ALOS PALSAR RTC DEM most consistently
124   matched the extent (red line) and depth of the new debris cone deposited as determined by our field
125   observations (Figure 3).
126
127   Our team was unable to locate the event on any seismographs, most likely related to the absence of
128   instrumentation in this part of the eastern Himalayas. Based upon direct field observations as well as
129   satellite imagery, the avalanche had clearly blocked and temporarily dammed the water from the
130   Nupchu Khola (river) at its onset, which was nevertheless able to cut down through the ice and
131   sediment deposited to form a steep canyon estimated at >10 m depth. The presence of shrubs (e.g., *J.*
132   *indica*) fully stripped of their bark was testimony to the high velocities of the flood- and meltwater
133   produced by frictional forces during the event, a phenomenon reported for other rockfall-induced
134   landslides in Nepal (Byers et al. 2019).
135
136   **5 Discussion**
137
138   Interestingly, individuals in the community of Kampuchen, only 5 km downstream of the event, were
139   unaware of the avalanche. Yak herds had already returned from the high pastures to the village by
140   early August, the community was busy harvesting potatoes and preparing for the fall tourist season,
141   and no obvious changes in the Nupchu Khola had been observed (e.g., Kargel 2014 for a description of
142   changes in the Seti Kosi prior to the catastrophic flooding of 5 May 2012). Thus, authorities in
143   Taplejung and Kathmandu were also unaware of the event as of September 2022, which is typical of
144   many large-scale cryospheric events in remote regions of the Himalayas (e.g., Byers et al. 2022).

145   Still, the acceleration of torrent-like pulses of debris upon the historic debris cone since 2020 suggests
146   that these events may be linked to contemporary warming trends, similar to those that may have
147   triggered larger-scale mass wasting events elsewhere in the Himalaya (e.g., Shugar et al. 2021; Kääb et
148   al. 2021; Taylor et al. 2023). The frequency of such ice-debris flow events within the KCA region, and
149   more broadly across the Himalaya, is unknown. However, with projections of continued warming in
150   these regions (e.g., Lalande et al. 2021), a more systematic approach to determining their historic
151   frequency, as well as a better understanding of their triggers, is warranted. After further evaluation,
152   vulnerable villages, such as Kampuchen, may wish to consider the installation of preventative

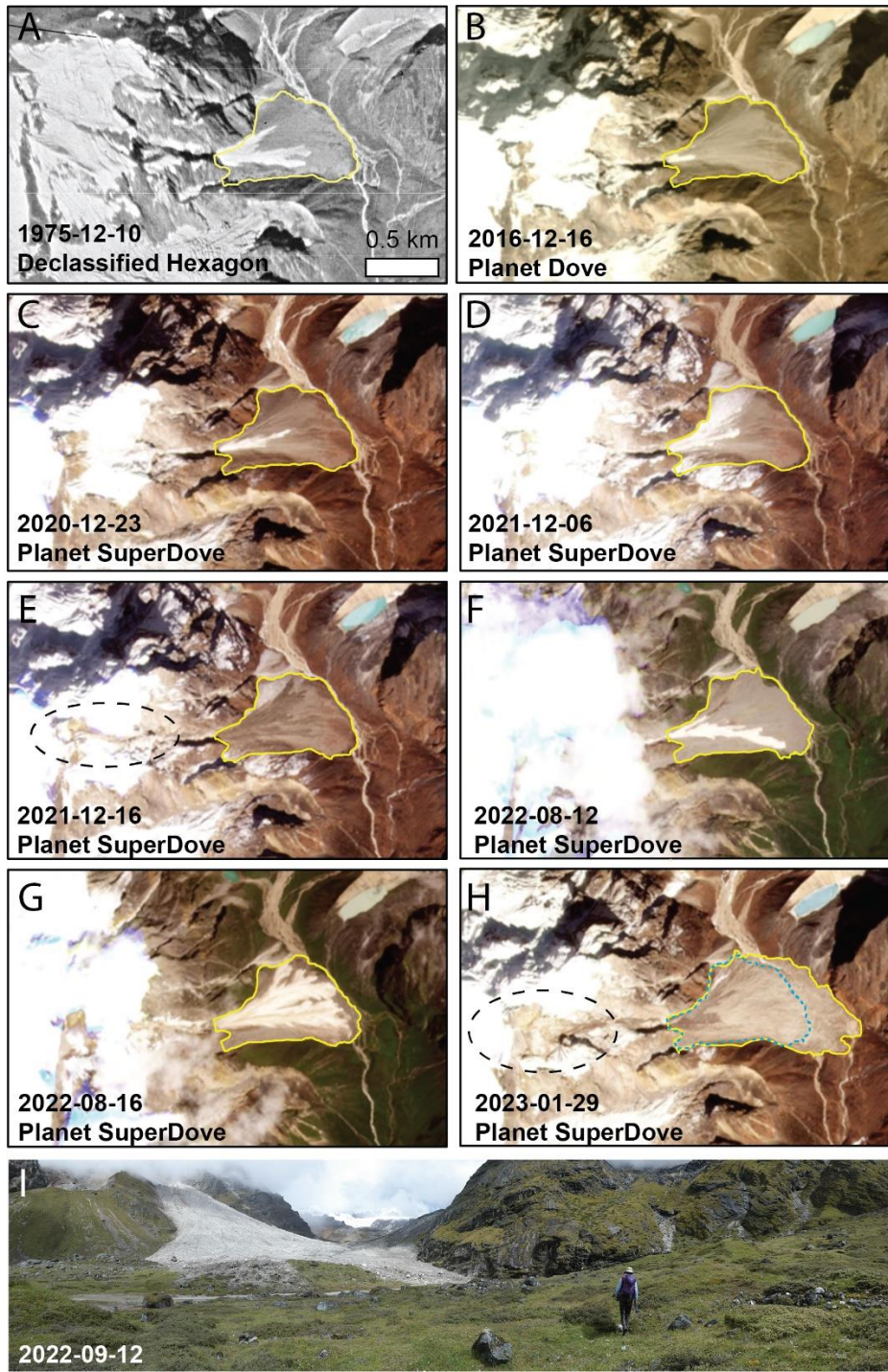
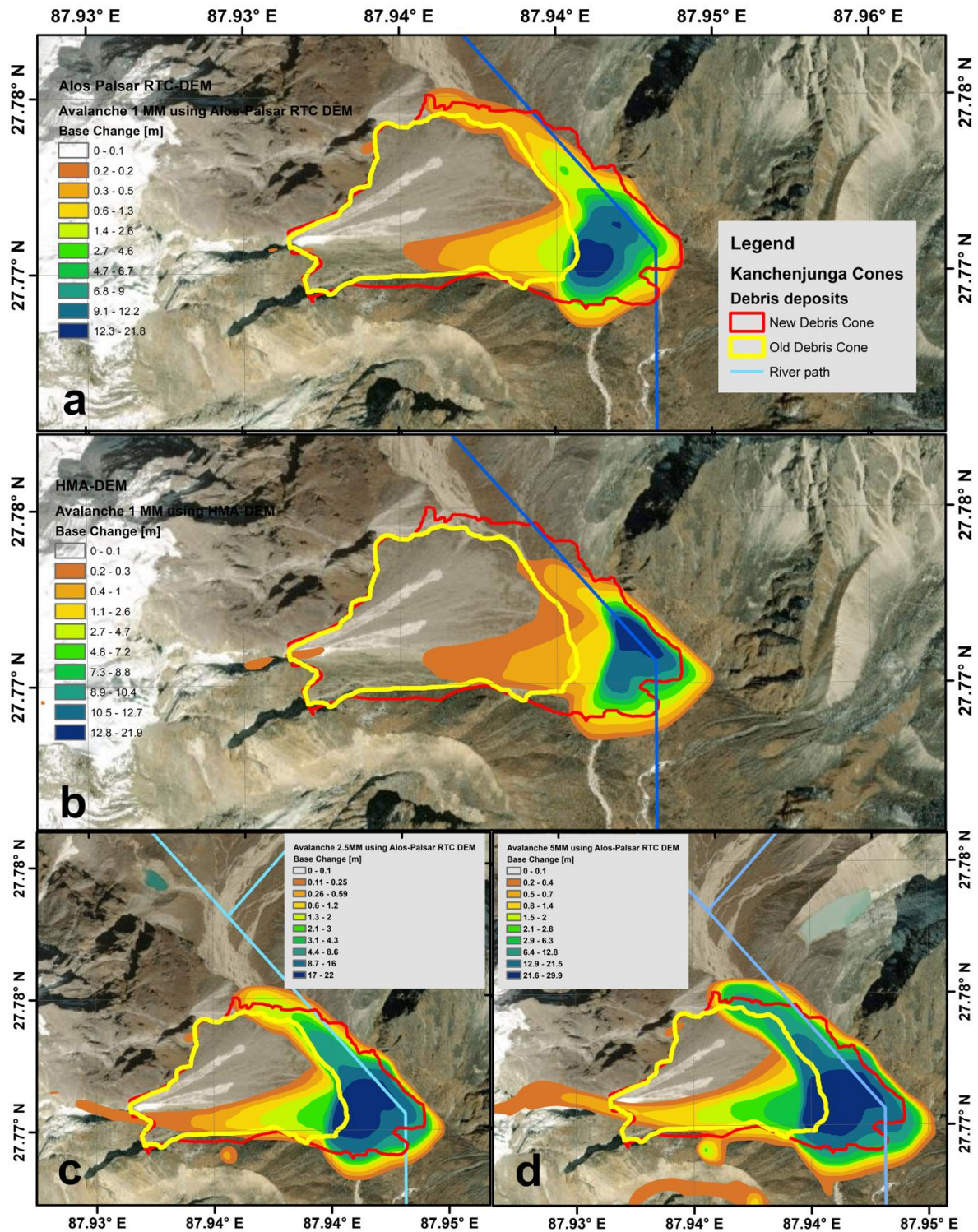



Figure 2. Time series satellite images showing the periodic occurrence of surficial debris flows upon the original deposition. These appear to have accelerated in both frequency in magnitude beginning several years ago, leading up to the main event that occurred between 16 and 21 August 2022. Blue dashed outline in panel H is the 1975 outline of the debris cone, while the dashed black circle identifies the failure zone. The photograph at the bottom provides an oblique view of the ice/debris avalanche about three weeks after it occurred (photograph by A. Byers). Panel H shows an image from early 2023, as imagery from immediately after the ice-avalanche in mid-August 2022 were partially obscured by clouds (KH-9 imagery courtesy of USGS; Planet Dove and SuperDove imagery courtesy of Planet Lab PBC).

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164 **Figure 3. Base change modeled with R.Avaflow for three different avalanche volumes: (a) 1 x10⁶ m³ using an**
165 **ALOS PALSAR RTC DEM, (b) 1 x10⁶ m³ using the void filled HMA-DEM, (c) 2.5 x10⁶ m³ (bottom left) using an**
166 **ALOS PALSAR RTC DEM, and (d) 5 x10⁶ m³ (bottom right) using an ALOS PALSAR RTC DEM. Of the three**
167 **estimates and 2 DEMs, 1 x 10⁶ m³ using an ALOS PALSAR RTC DEM most consistently matched the extent and**
168 **depth of the new debris cone deposited in August 2022 (red line; the yellow line represents the extent of the**
169 **historic debris cone).**

170 floodwater diversion mechanisms, such as the rock-filled gabion walls currently protecting tourist
171 lodges in the Mt. Everest region (e.g., Rounce et al. 2017; Byers et al. 2022) using participatory
172 processes as outlined in Watanabe et al. (2016).
173
174 **5 Conclusion**
175
176 Beginning in 2020, a series of small-to-medium, torrent-like pulses commenced upon a historic debris
177 cone located approximately 2 km down valley from the lake, culminating in a relatively large
178 avalanche event that occurred sometime between 16 and 21 August 2022. The August 2022 event
179 deposited debris with an area of 0.6 km^2 and estimated volume in the order of 10^6 m^3. No fatalities
180 from the event occurred because of the absence of humans and livestock in the vicinity when the
181 event occurred. Likewise, no impoundment of the Nupchu Khola, and formation of a potentially
182 dangerous backwater lake, occurred as a result of debris blockage, although such scenarios happen
183 routinely in high mountain environments.
184
185 The improvement of remote area event reporting mechanisms, especially to authorities in the capital,
186 Kathmandu, could help with the development of hazard mitigation technologies and response.
187 Likewise, more systematic monitoring of cryospheric events by scientists, using remote sensing
188 platforms and hazard mapping tools, could help with the development of more effective early warning
189 systems for vulnerable communities, livestock, and adventure tourists. Ultimately, this could lead to a
190 minimization of losses and damage due to multi-hazard events.
191

192 *Data availability.* Declassified KH-9 Hexagon satellite imagery is available at
193 https://earthexplorer.usgs.gov/. Planet Dove and SuperDove satellite imagery is available
194 at https://www.planet.com/explorer/. The ALOS PALSAR Radiometric Terrain Corrected high-res DEM
195 "AP_13152_FBD_F0540_RT1" is available at https://search.asf.alaska.edu/. The High Mountain Asia 8-
196 meter DEM is available at https://nsidc.org/data/hma_dem8m_ct/versions/1#anchor-1
197
198 *Author contributions*. ACB conceived the study and wrote the original narrative, with contributions
199 from MS-V, DS, DM, MBC, and RA. MBC created Figure 1, DS and RA created Figure 2, and MS-V
200 created Figure 3. MS-V conducted the numerical simulations of avalanche volumes shown in Figure 3.
201 All authors revised and contributed to the final manuscript.
202
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References

ASF DAAC 2014. ALOS PALSAR Radiometric Terrain Corrected high res; Includes Material © JAXA/METI 2008 Accessed through https://search.asf.alaska.edu/on 11 February 2023. https://doi.org/10.5067/ 10.5067/Z97HFCNKR6VA

Byers, A.C., Shugar, D., Chand, M., Portocarrero, C., Shrestha, M., Rounce, D., and Watanabe, T.: Three recent and lesser-known glacier-related flood mechanisms in high mountain environments. Mountain Research and Development, 42(2):A12-A22, 2022. https://doi.org/10.1659/MRD-JOURNAL-D-21-00045.1

Byers, A.C., Chand, M.B., Lala, J., Shrestha, M., Byers, E.A., and Watanabe, T. 2020. Reconstructing the history of glacial lake outburst floods (GLOF) in the Kanchenjunga Conservation Area, east Nepal: an interdisciplinary approach. Sustainability 2020, *12*, 5407. https://www.mdpi.com/2071-1050/12/13/5407

Byers, A.C., Rounce, D.R., Shugar, D.H. and Regmi, D.: A rockfall-induced glacial lake outburst flood, upper Barun valley, Nepal. Landslides (2019) 16: 533, 2019. https://doi.org/10.1007/s10346-018-1079-9

Dehecq, A., Gardner, A.S., Alexandrov, O., McMichael, S., Hugonnet, R., Shean, D., and Marty, M.: Automated processing of declassified KH-9 Hexagon satellite images for global elevation change analysis since the 1970s, Frontiers Earth Science, Vol. 8, 09 November, 2020. https://doi.org/10.3389/feart.2020.566802

Freshfield, D.W.: Round Kangchenjunga: A Narrative of Mountain Travel and Exploration (historic reprInt), 1903. www.forgottenbooks.com

Hooker, J.D.: Himalayan Journals Vol. 1, 1854, Orlando: The Perfect Library (historic reprint).

Kääb, A., Jacquemart, M. n., Gilbert, A., Leinss, S., Girod, L., Huggel, C., Falaschi, D., Ugalde, F., Petrakov, D., Chernomorets, S., Dokukin, M., Paul, F., Gascoin, S., Berthier, E. and Kargel, J.: Sudden large-volume detachments of low-angle mountain glaciers: more frequent than thought? Cryosphere 15(4), 1751–1785, 2021. https://doi:10.5194/tc-15-1751-2021

Kandel, P., Chettri, N., Chaudhary, R.P., Badola, H.M., Gaira, K.S., Wangchuk, S., Bidha, N., Uprety, Y., Sharma, E.: Plant Diversity of the Kangchenjunga Landscape, Eastern Himalayas. Plant Diversity, Volume 41, Issue 3, 2019, pp. 153-165, 2019. https://doi.org/10.1016/j.pld.2019.04.006

Kargel J.: One scientist's search for the causes of the deadly Seti River flash flood. Earth Observatory, 24 January, 2014. https://earthobservatory.nasa.gov/blogs/fromthefield/2014/01/24/setiriverclues/; accessed on 15 December 2022.

Lalande, M., Ménégoz, M., Krinner, G., Naegeli, K., and Wunderle, S.: Climate change in the High Mountain Asia in CMIP6, Earth Syst. Dynam., 12, 1061–1098, https://doi.org/10.5194/esd-12-1061-2021, 2021.

266 Maurer, J.M., Schaeffer, J.M., Rupper, S., and Corley, A.: Acceleration of ice loss across the Himalayas
267   over the past 40 years. Science Advances, Vol 5, Issue 6, 2019. https://doi: 10.1126/sciadv.aav7266

269 Mergili, M., Fischer, J. T., Krenn, J. y Pudasaini, S. P.: R.avaflow v1, an advanced open-source
270   computational framework for the propagation and interaction of two-phase mass flows, Geosci.
271   Model Dev., 10(2), 553–569, 2017. https://doi:10.5194/gmd-10-553-2017.

273 Mergili, M. and Pudasaini, S.P., 2014-2023. r.avaflow - The Mass Flow Simulation Tool.
274   https://www.avaflow.org

276 Racoviteanu, A.E., Arnaud, Y., Williams, M.W., and Manley, W.F.: Spatial patterns in glacier
277   characteristics and area changes from 1962 to 2006 in the Kanchenjunga–Sikkim area, eastern
278   Himalaya. The Cryosphere, 9, 505–523, 2015. www.the-cryosphere.net/9/505/2015/
279   doi:10.5194/tc-9-505-2015.

281 Shean, D. (2017). High Mountain Asia 8-meter DEMs Derived from Cross-track Optical Imagery.
282   Boulder, CO: NASA NSIDC DAAC: NASA National Snow and Ice Data Center Distributed Active Archive
283   Center. https://doi.org/10.5067/0MCWJJH5ABYO. Accessed on July 20, 2023.

285 Taylor, C., Robinson, T.R., Dunning, S., Carr, R. and Westoby, M.: Glacial lake outburst floods threaten
286   millions globally. Nature Communications 14, 487 (2023). https://doi.org/10.1038/s41467-023-
287   36033-x

289 Thapa, R: Kanchenjunga: The Unique Gift of Nature. Kathmandu: Kanchan Printing Press, published by
290   Phupu Chowang Sherpa, 2009.

292 Watanabe, T., Khanal, N.R., and Gautam, M.P.: The Nangama glacial lake outburst flood occurred on
293   23 June 1980 in the Kanchanjunga area, eastern Nepal. Ann. Hokkaido Geogr. Soc., *72*, 13–20, 1998.
294   DOI:10.14917/hgs1959.1998.13.

296 Watanabe, T., A. C. Byers, M, A. Somos-Valenzuela and D. C. McKinney: The need for community
297   involvement in glacial lake field research: the case of Imja Glacial Lake, Khumbu, Nepal Himalaya.
298   Chapter 13. In: Singh, R. B., Schickhoff, U., and Mal, S. (eds.): *Climate Change, Glacier Response, and*
299   *Vegetation Dynamics in the Himalaya: Contributions Toward Future Earth Initiatives*, Springer
300   International Publishing Switzerland, pp. 235-250, 2016, doi:10.1007/978-3-319-28977-9_13

302 Zhang, T., Wang, W., Shen, Z., Zhan, N., Wang, Z. and An, B.: Understanding the 2004 glacier
303   detachment in the Amney Machen Mountains, northeastern Tibetan Plateau, via multi-phase
304   modeling. Landslides, (October), 2022. https://doi:10.1007/s10346-022-01989-2.