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5 **1. Extended Data**

Figure #	Figure title	Filename	Figure Legend
	One sentence only	This should be the name the file is saved as when it is uploaded to our system. Please include the file extension. i.e.: <i>Smith_ED_Fi_1.jpg</i>	If you are citing a reference for the first time in these legends, please include all new references in the Online Methods References section, and carry on the numbering from the main References section of the paper.
Extended Data Fig. 1	Extended Data Fig 1. Landsat satellite imagery used to map debris cover.	Herreid_ED_01_Fig1.jpg	The footprint of each manually selected Landsat image is shown colored by the date of acquisition. The histogram inset shows the number of scenes per year differentiated by sensor and is broken down per region in the Supplemental Information.
Extended Data Fig. 2	Extended Data Fig 2. Landsat image coverage with no overlap.	Herreid_ED_02_Fig2.jpg	Landsat image footprints over Alaska and Western Canada are outlined and colored by acquisition data illustrating the preference given to more recent imagery and the removal of overlapping image area.
Extended Data Fig. 3	Extended Data Fig 3. Amending the RGI v6.0.	Herreid_ED_03_Fig3.jpg	Southern Andes as an example of the manual steps taken to identify and remove FP glacier error, area in shadow and cloud covered area; and identify and add FN errors in every RGI region. The wider shapes, or lassos, were used to tag enclave shapes initially mapped as ‘debris cover’ with a specific error

			or true (by omission) classification. This lasso approach enables the manual work conducted in this study to be used again in future inventories with any desired modifications.
Extended Data Fig. 4	Global debris cover results and errors in RGI v6.0 presented as regional percentages.	Herreid_ED_04_Table 1.jpg	All values are given for glaciers with a surface area greater than or equal to 1 km ² that fall within the considered spatial domain. ‘% RGI6.0 considered’ is unedited RGI v6.0 glacier area with i. glaciers smaller than 1 km ² removed and ii. area outside of the Landsat image composite (Extended Data Fig. 1) removed divided by entirely unaltered RGI v6.0 glacier area. ‘% SamRGI considered’ is the edited glacier area within the Landsat image composite divided by the edited glacier area inside and outside of the Landsat image composite.
Extended Data Fig. 5	Global debris cover results and errors in the RGI v6.0 presented as areas (km ²).	Herreid_ED_05_Table 2.jpg	Glacier area includes corrections to the RGI. These results exclude glaciers with a surface area less than 1 km ² . Glacier area in shadow, including other visually uncertain shapes classified as debris, were removed from the debris map but not removed from the RGI.
Extended Data Fig. 6	Extended Data Fig 4. Estimation of the equilibrium line from mapped debris cover.	Herreid_ED_06_Fig4.jpg	Map view and cross-section cartoon illustrating the method used in this study to estimate the position of the equilibrium line for glaciers with 7% debris cover and/or >10 km ² debris-covered area. Equilibrium line is estimated by locating the upper-most debris exposure, extending the point of exposure to the full glacier width and adjusting the position up-glacier by a factor of <i>d</i> . <i>d</i> is the glacier specific distance between the true equilibrium line and the first down-glacier emergence of englacial debris.
Extended Data Fig. 7	Extended Data Fig 5. Cases where the	Herreid_ED_07_Fig5.j	Landsat image of glaciers in Svalbard (a) and corresponding results from this study (b) showing examples of where

	equilibrium line location estimates are incorrect.	pg	equilibrium line estimates (yellow line) derived from mapped debris cover fails. Equilibrium lines shown on grey glaciers did not meet the 7% debris cover and/or >10 km ² debris-covered area criteria and were not included in any further metric derivation or results. Glaciers shown as blue met the criteria to be included in the study but also are shown to have errors. The source for error include (1) sparse debris cover producing nonsensical equilibrium lines; (2) imperfect flow divides drawn in ambiguous cases within RGI v6.0 causing unphysical equilibrium line estimates; (3) the unusual case where debris cover is present up-glacier but is not sufficiently present at lower reaches of the glacier to be detected by the debris mapping algorithm; (4) a portion of a glacier's ablation zone is debris free and big enough to cause the glacier width buffer to inaccurately extend the ablation zone area to encompass the full width of the glacier. While this sample region was selected due to a concentration of errors, (5) shows a location where equilibrium line location was predicted as intended.
Extended Data Fig. 8	Extended Data Fig 6. Comparison between the global debris map presented here and the global debris map from (ref. ¹⁸).	Herreid_ED_08_Fig6.j pg	Error, true positive rate and precision are calculated under the assumption that results from this study are correct. The basis of this assumption is the additional manual editing that was conducted within this study, where (ref. ¹⁸) used unaltered RGI v6.0. Greenland was excluded from the comparison due to the different spatial domains considered. The values used to make this figure are given in the Supplemental Information.
Extended Data Fig. 9	Extended Data Fig 7. Examples illustrating errors in the RGI and (ref. ¹⁸).	Herreid_ED_09_Fig7.j pg	Two example locations are shown to illustrate a setting where heavy editing to the RGI was required (Central Asia) and almost no editing of the RGI was required (Alaska). The bottom two panels show the comparison of results from this study and those of (ref. ¹⁸). A clear undercounting of debris by (ref. ¹⁸) is apparent in both regions where in Alaska the methods of (ref. ¹⁸) are examined without influence from the

			RGI editing conducted in this study while the errors in Central Asia show a compound error in (ref. ¹⁸) composed of both an undercounting of true debris cover and an over counting where off-glacier area is erroneously classified as debris cover.
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6 **2. Supplementary Information:**

7 **A. Flat Files**

Item	Present?	Filename	A brief, numerical description of file contents. <i>i.e.: Supplementary Figures 1-4, Supplementary Discussion, and Supplementary Tables 1-4.</i>
Supplementary Information	Choose an item.	Herreid_R2_SI.pdf This should be the name the file is saved as when it is uploaded to our system, and should include the file extension. The extension must be .pdf	Supplementary Text Figures S1 to S6 Tables S1 to S4 Description of Data S1 to S3 Supplementary References
Reporting Summary	Choose an item.		

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The state of rock debris covering Earth's glaciers

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18 **Rock debris can accumulate on glacier surfaces and dramatically reduce glacier melt. The**
19 **structure of a debris cover is unique to each glacier and sensitive to climate. Despite this,**
20 **debris cover has been omitted from global glacier models and forecasts of their response to**
21 **a changing climate. Fundamental to resolving these omissions is a global map of debris**
22 **cover and an estimate of its future spatial evolution. Here we use Landsat imagery and a**
23 **detailed correction to the Randolph Glacier Inventory to show that 7.3% of mountain**
24 **glacier area is debris-covered and over half of Earth's debris is concentrated in three**
25 **regions: Alaska (38.6% of total debris-covered area), Southwest Asia (12.6%) and**
26 **Greenland (12.0%). We use a set of new metrics including *stage*, the current position of a**
27 **glacier on its trajectory towards reaching its spatial debris cover carrying capacity, to**
28 **quantify the state of glaciers. Debris cover is present on 44% of Earth's glaciers and**
29 **prominent ($>1.0 \text{ km}^2$) on 15%. 20% of Earth's glaciers have a substantial percentage of**
30 **debris cover for which net *stage* is 36% and the bulk of individual glaciers have evolved**
31 **beyond an optimal moraine configuration favorable for debris cover expansion. Use of this**
32 **dataset in global scale models will enable improved estimates of melt over 10.6% of the**
33 **global glacier domain.**

34 A layer of rock debris on the surface of a glacier causes a diminishing sub-debris melt rate as the
35 layer thickness varies from ~ 2 cm to meters thick¹⁻³. This relation has been established since
36 1959, yet a consideration of supraglacial rock debris has been a long-standing omission from
37 global scale glacier models⁴ often citing its heterogeneous properties and assumed sparse global
38 distribution as justification. Beyond the problem of resolving basic debris geometry, as a debris
39 cover increases in extent it can support the development of ice cliffs and supraglacial ponds
40 which have been shown to accelerate the local melt rate^{5,6} and add complexity to the advanced

41 stages of debris cover evolution⁷. While an omission of debris cover was necessary to arrive at
42 the first operative global scale models, a consideration of debris cover, summed over Earth's
43 glaciers, has the potential to reveal that earlier estimates of glacier-sourced eustatic sea level rise
44 were too high. Additionally, hydrological models will likely underestimate the longevity of
45 glacier sourced water resources if debris cover, and its evolution, is neglected.

46 While the structure of the debris present on any one glacier is a unique and complex function of
47 many local factors including the surrounding geology, topographic relief and glacier dynamics⁸,
48 a consensus of studies from around the world show a spatial expansion of debris cover and link
49 this change to a warming climate⁹⁻¹⁶. Between the evidence that debris cover is expanding and its
50 omission in global glacier models, there are three remaining fundamental unknowns that need to
51 be resolved in order to close this knowledge gap: the spatial distribution, thickness and 3-D
52 evolution of supraglacial debris. Very few prior studies have quantified debris cover at a global
53 scale^{17,18}. These studies relied on fully automated, big data techniques that either lack agreement
54 to repeat measurements (Extended Data Fig. 6, 7, Supplementary Material) or were not
55 published. A global scale consideration of the trajectory debris cover may follow as it evolves in
56 the future has never been addressed. Here, we take the opposite of a big data approach and apply
57 a semi-automated method to carefully selected satellite images with iterative and manually
58 intensive steps to mitigate several sources of error that are difficult to automate including
59 inaccurate/outdated glacier outlines, cloud cover and topographic shading. We use these results
60 to address two of the global unknowns: the spatial distribution and 2-D evolution trajectory of
61 debris cover.

62

63 **Global distribution of debris cover**

64 Multispectral satellite imagery and a map of glacier area can be used as input to a simple image
65 segmentation approach to map debris cover^{19,20}. The strong color contrast between rocks and
66 glacier ice, firn and snow enables a robust and repeatable method to map debris cover, provided
67 the glacier map is accurate and the imagery is controlled for factors including seasonal snow and
68 cloud cover (Methods Section 1.1). With the 2014 release of the global Randolph Glacier
69 Inventory²¹ (RGI), hereafter referring to version 6.0 (ref. ²²), it became feasible to map debris
70 cover globally using this method¹⁸. However, a preliminary qualitative investigation for this
71 study suggested that the RGI inconsistently constrained the glacier area visible in a manually
72 selected, overlap-free global coverage of Landsat imagery (n = 255, acquired between 1986-
73 2016, median = 2013, Methods Sections 1.1-1.3, Extended Data Fig. 1, 2 Supplemental
74 Information), and thus was of insufficient quality to map debris cover (Extended Data Fig. 7). To
75 address and quantify this deficiency, we updated the RGI (with a conditional inclusion of the
76 entire Greenland ice sheet, exclusion of Antarctica and exclusion of all glaciers with a surface
77 area <1 km², Methods Section 1.4, 1.10) by generating a first iteration global debris cover map
78 which defined the shape of all non-bare-ice area within the RGI. We then, in a time intensive
79 step, manually differentiated these shapes between true positive debris cover, land that is not
80 glacier (RGI false positive) and topographically shaded area (Methods Sections 1.4-1.10,
81 Extended Data Fig. 3, 8). Glacier area missing from the RGI (false negative glacier area) was
82 digitized manually. False positive and false negative errors within the RGI summed to 11,483
83 km² or 3.3% of glacier area (Extended Data Tables 1, 2) and their removal along with shaded
84 and clouded area enabled the derivation of a final, refined and temporally consistent glacier and
85 debris cover map showing 7.3% of Earth's mountain glacier area is covered by rock debris (Fig.
86 1, Methods Section 1.11, Extended Data Tables 1, 2). This result is distinctly higher than the

87 only previously published global debris cover map¹⁸. A comparison analysis with [18] shows a
88 systematic undercounting of debris cover where 51% of the debris cover mapped in this study
89 was missed by [18] and 25% of the debris mapped by [18] was not classified as debris in this study
90 (Extended Data Fig. 6, 7, Supplemental Information). A comparison analysis with the regional
91 debris cover map from [23], who included debris cover in a full glacier model for all High
92 Mountain Asia, shows a higher, 81% coincidence with the debris cover mapped in this study and
93 a false discovery rate of 29% (Supplemental Data). Both comparison analyses with [18] and [23]
94 overcount error where these studies correctly identified debris cover that is missed in this study.
95 Of the glaciers on Earth with a surface area $>2 \text{ km}^2$, 44% have some debris cover ($>0.1 \text{ km}^2$) and
96 15% have a prominent debris cover ($>1.0 \text{ km}^2$; Fig. 1a). 20% of Earth's glaciers with a surface
97 area $>2 \text{ km}^2$ have a 'substantial' debris cover ($>7\%$ debris-covered and/or $>10 \text{ km}^2$ of debris)
98 which we define to make debris cover dependent calculations. Considering only this 20% of
99 Earth's glaciers, the percentage of debris-covered area is 14% and with a further constraint
100 considering only ablation zone area (Methods Section 1.14, Extended Data Fig. 4, Supplemental
101 Information), debris cover *stage* is 36%. *Stage* ranges from 0 to 1, where a *stage* of 1 means the
102 entire ablation zone of a glacier is covered in debris. This corresponds to reaching the full, 2-D
103 'debris cover carrying capacity' of a glacier because debris-covered area cannot expand further
104 without up-glacier migration of the equilibrium line.

105 Alaska, South Asia West and Greenland have the greatest absolute debris-covered area among
106 Earth's glacierized regions and constitute over half of Earth's total supraglacial debris coverage
107 (Fig. 1, Extended Data Table 1). However, when considering regional percentages of debris-
108 covered area, the debris structures within these three top regions reflect markedly different states,
109 where Greenland has a sparse debris cover spread over a wide glacierized area and South Asia

110 West has a more advanced debris cover distributed over relatively sparse glacierization
111 (Extended Data Table 1). Alaska has a similar percentage of debris cover as South Asia West but
112 with more glacier and debris-covered area by a factor of three (Extended Data Table 1, 2).
113 We find that an exponential relation describes an increased regional percentage of debris-covered
114 glacier area with decreasing distance from the equator (Fig. 2). This relation suggests that
115 warmer climatic zones are more dynamic and conducive to supraglacial debris production, yet
116 orographic factors (e.g. mountain range age, relief and lithology) may be able to offset a region
117 from this relation as shown by outlying regions in Fig. 2, specifically Alaska.

118

119 **Debris cover state**

120 To further decompose regional variability, debris coverage and evolutionary state was derived
121 for each individual glacier where certain surface area and debris cover criteria were met
122 (Methods Section 1.13). Two metrics common in glaciological literature were calculated:
123 *percent debris-covered*, and the *accumulation zone area ratio (AAR)*²⁴. Four new metrics were
124 also calculated that, together, summarize debris cover state: *stage* (described above), *debris*
125 *expansion potential*, *future debris expansion* and *moraine abundance* (Fig. 3).

126 *Debris expansion potential* is the length of the debris cover-bare ice boundary divided by the
127 perimeter of the debris cover. Drawing on an assumption that newly debris-covered area will
128 share a boundary with existing debris cover (Supplemental Information), the debris cover-bare
129 ice boundary is the location with the highest potential to expand ‘inward’, flipping formerly bare
130 ice area to debris-covered. The length of this boundary, and thus the glacier normalized *debris*
131 *expansion potential* value, will increase during a phase of moraine formation where there are

132 potentially several discrete and parallel medial moraines. In a warming climate favorable to an
133 expanding debris cover, *debris expansion potential* will, at some point in time, reach a glacier
134 specific maximum value (≤ 1) at the glacier's peak abundance of discrete moraine bands. Finally,
135 *debris expansion potential* will decrease as once discrete medial moraines coalesces to form a
136 continuous debris cover and reach the spatial debris cover carrying capacity (*stage* = 1). At this
137 point, *debris expansion potential* will have converged to the length of a future equilibrium line
138 divided by the future ablation zone perimeter. The value of *debris expansion potential* at this
139 future convergence is termed the *future expansion potential* which we coarsely estimate for each
140 glacier assuming a static equilibrium line and glacier geometry through time.

141 *Moraine abundance* is the ratio of a glacier's debris cover perimeter and the perimeter of its
142 ablation zone. *Moraine abundance* has no structural upper limit and will increase with the
143 abundance and length of distinct medial moraines. This metric is identical to *stage* except that it
144 is expressed in terms of shape perimeters rather than areas and is thus proportional to moraine
145 structure complexity. While *debris expansion potential* is a ratio of two debris related terms,
146 *moraine abundance* is normalized to a debris independent term, the ablation zone area, making it
147 a summary metric that includes aspects of both *stage* and *debris expansion potential*. The time
148 evolution of *moraine abundance* will follow a similar trajectory to *debris expansion potential*,
149 but with convergence to a value of 1 as debris fills the entire ablation zone (reaching the spatial
150 carrying capacity, *stage* = 1) and the two perimeters become identical in shape and length.

151 While *percent debris-covered* is the universally used metric to describe debris cover, it does not
152 converge to a known shape or quantity and it is less sensitive to debris cover changes due to the
153 inclusion of the accumulation zone in normalization. A selection of four glaciers from around the
154 world with similar surface areas were selected to show both an example of mapped quantities

155 with their corresponding metric values as well as snapshot examples, present on Earth today, of
156 the debris cover evolution progression described above (Fig. 3). The progression of moraine
157 structures, from sparse moraines to a near-complete debris cover, is reflected in both *debris*
158 *expansion potential* and *moraine abundance* and the progression in overall debris cover is
159 captured by *stage*. *Percent debris-covered* fails to capture an evolution progression and reaches
160 an inconspicuous value of 40% even though nearly every part of the glacier that could be debris-
161 covered, is debris-covered. This suggests that, provided an accurate estimate of the equilibrium
162 line can be made (Extended Data Fig. 5, Supplemental Information), the set of metrics derived
163 here should complement or replace results presented as *percent debris-covered*.

164 Combined, these new metrics transform 2-D structural complexities into a set of 0-D values that
165 can easily integrate into a global scale model. These metrics, computed per glacier, are
166 summarized at a global scale by regional median and percentile statistics (Fig. 4). An isolation of
167 ‘advanced’ *stage* glaciers, delimited arbitrarily by a *stage* of 0.7, shows their concentrated
168 abundance in Alaska, High Mountain Asia and New Zealand (Fig. 4a). However, for most
169 regions, advanced *stage* glaciers fall outside of the 90% percentile and are thus currently rare
170 within the glacier domain established in the RGI.

171

172 **Debris cover evolution trajectory**

173 Under the frequently stated assumption that debris-covered area will continue to expand in a
174 warming climate^{25,26}, *stage* can be considered a proxy for time. A timescale on the order of 100s
175 of years of gradual debris cover expansion^{9,27} is likely needed to sum to distinct changes in *stage*,
176 e.g. a transition from sparse debris cover to a glacier’s peak abundance of medial moraines. This

177 association with time allows the current global distribution of glaciers exhibiting different values
178 of *stage* to characterize the trajectory of debris cover evolution (Fig. 5,6).

179 Considering the global distribution of glaciers, continuous space-for-time trajectories of *debris*
180 *expansion potential* (Fig. 5) and *moraine abundance* (Fig. 6) were derived. For both metrics, the
181 x-axis distance from the maximum value of the trajectory curve to the peak point density,
182 interpreted as a summary value of the bulk regional or global current state, offers an estimate of
183 the debris evolution past maximum (EPM). The remaining x-axis distance to reach a *stage* of 1 is
184 termed the distance to carrying capacity (DCC). On a global scale, most glaciers with debris
185 cover (not weighted by glacier area) have passed a moraine formation maximum (EPM would be
186 zero or negative otherwise) and are over halfway to reaching the spatial debris cover carrying
187 capacity where $DCC = 0.4$ for both metrics (Fig. 5, 6).

188 South Asia East, which has the most negative mass balance of the three High Mountain Asia
189 RGI regions²⁸, also has the most advanced debris cover state on Earth where DCC is 0.3 and 0.2
190 for *debris expansion potential* and *moraine abundance*, respectively. As a whole, High Mountain
191 Asia hosts the highest abundance of advanced *stage* glaciers (Fig. 4a). While the high relief and
192 climatic setting within High Mountain Asia might be conducive to debris production²⁹⁻³¹, it is
193 unknown if glaciers in other regions on Earth will eventually reach a similarly advanced state in
194 a continued warming climate. Evidence suggests glacier recession couples with an increase in
195 englacial debris exhumed to the surface^{25,32} and an increase in debris supplied from unstable
196 slopes exposed from lowering glacier surfaces²⁹. For glaciers trending towards cessation on the
197 downward limbs of Fig. 5 and 6, a possible outcome may be the decoupling of remnant, no
198 longer internally deforming, debris-free accumulation zones from heavily debris-covered tongues
199 that could transition to a rock glacier state (Fig. 5, Supplemental Information). Other possible

200 trajectories include rapid glacier shrinkage that outpaces debris cover evolution reducing its
201 overall impact, or a different trajectory that breaks the currently held assumption that the extent
202 of debris cover will expand in a warming climate^{25,26}. The remaining 80% of glaciers (by
203 number, with a surface area $>2 \text{ km}^2$ and a debris cover $<7\%$ and/or $<10\text{km}^2$) where rock debris is
204 not a prominent feature may establish a debris cover in the future, or may be on an alternative
205 trajectory largely free from the effects of debris cover. Resolving this unknown will be of
206 growing significance in a continued warming climate for long-term projections of glacier
207 changes, water resources and sea level rise.

208 For the 20% of glaciers that have a substantial debris cover, this study establishes the state of
209 debris cover from a global, regional and individual glacier scale in a publicly available database
210 and provides the first estimates of the long-term trajectory of debris cover evolution. We are able
211 to show that a significant portion of the literature focused on “debris-covered glaciers” was
212 biased towards advanced *stage* glaciers (e.g. Langtang, Noghumpa, Khumbu and Miage glaciers;
213 identified in Fig. 5, 6), which may have limited relevance if used to extend a process
214 understanding to the bulk of debris-covered glacier ice. Of glaciers with a surface area $>2 \text{ km}^2$,
215 4.1% have a *stage* greater than 0.7 encompassing 12.9% of the total 29,182 km^2 of debris-
216 covered area. The remaining 87.1% of debris-covered ice and its evolution through time is where
217 field-based and modeling efforts might be better focused. We now provide a near census dataset
218 the research community can draw from and contextualize the relative importance of debris cover
219 and the spectrum of debris cover configurations found on Earth’s glaciers. Results also reveal
220 which limb of the debris evolution curves (Fig. 5, 6) each glacier falls on. This information can
221 aid numerical models of debris cover evolution by indicating if the model framework should
222 nucleate new debris³³ or expand existing debris³⁴. At a global scale, the combined factors of

223 surface debris cover and errors within the RGI suggest glacier melt models that neglect these
224 terms may have inaccurate solutions for melt over 10.6% of the global glacier domain. This
225 finding is compounded by the tendency of debris cover to be most abundant and thick at the
226 lower reaches of a glacier where melt rates would, in the absence of debris cover, be the
227 highest³⁵. Results from this study enable the removal of a modeled runoff signal from glacier
228 area that does not exist and provides the locations where a more sophisticated treatment of debris
229 modulated glacier melt is needed. A full integration of these terms will facilitate improved
230 projections of water resources from Earth's glaciers³⁶ and produce a more confident, and likely
231 lower, estimate of glacier-sourced eustatic sea level rise.

232

233 **Data availability**

234 This study relied on publicly available data from the NASA/USGS Landsat program:
235 <https://earthexplorer.usgs.gov/>. The glacier and debris cover data that support the findings of this
236 study are available at <https://doi.org/10.5281/zenodo.3866466> and are described in the
237 Supplemental Information.

238

239 **Code availability**

240 All of the code written for this study is available from the corresponding author upon request.

241

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332

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336

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344 **Author contributions**

345 S.H. designed and conducted the study, interpreted the results and wrote the manuscript. F.P.
346 secured the institutional funding, helped interpret the results and contributed to writing the
347 manuscript.

348

349 **Competing interests**

350 The authors declare no competing interests.

351

352 **Supplementary information**

353 Supplementary Text

354 Figures S1-S6

355 Tables S1-S4

356 Description of Data S1 to S3

358

359 **Fig. 1. Global distribution of supraglacial debris cover.** The fraction of glacier area covered
360 by rock debris is shown for each glacierized region on Earth along with false positive (FP) and
361 false negative (FN) errors that were identified and corrected within the RGI v6.0. The glacier
362 area considered in this study is shown as both the fraction of the RGI with errors and glaciers
363 smaller than 1 km² removed (SamRGI) and the unaltered RGI v6.0. The fraction ‘Earth’s
364 glaciers’ indicates the relative size of each region. **(a)** Cumulative distribution function of per
365 glacier debris cover for Earth’s glaciers with a surface area > 2 km² suggesting debris cover is
366 present (>0.1 km²) on 44% of Earth’s glaciers and prominent (>1.0 km²) on 15% of glaciers. **(b)**
367 The Greenland ice sheet is approximately a factor of 4.2 times the surface area of all mountain
368 glaciers combined.

369

370

371 **Fig. 2. Polar regions have less debris cover.** Exponential function, of the form $y=ae^{-bx}$, fit to
372 regional percent debris-covered glacier area and the absolute value of median latitude (grey bars
373 show full latitude range). Weighted by glacierized area (circle size shows glacierized area scaled
374 linearly). The blue curve is fit using all regions excluding Greenland, the black curve is fit using
375 all regions excluding Greenland and Alaska.

376

377 **Fig. 3. Source data composite images and examples from different locations on Earth with**
378 **different metric values.** Glaciers were selected based on similar surface area (Ayunnamat
379 Glacier an exception, 20 km² less than the other three), and exhibiting the spectrum of metric
380 values ordered (left to right) to show a conceptual progression of debris cover evolution.
381 Notably, the evolution of *moraine abundance* with respect to *stage* (values in grey and purple,
382 respectively) while the often reported metric *percent debris-covered* remains largely stable.
383 Latitude and longitude locate each glacier's centroid. Metric definitions and their constituent
384 glacier quantities are identified on Kangjaruo Glacier (28.428°N, 85.692°E, South Asia East)
385 which are color coded to each glacier's set of metric values. Equilibrium line is shown on the
386 Landsat composite images to illustrate the quality of this estimate.
387

388 **Fig. 4. Regional distributions of six metrics relating to glacier health and debris cover**
389 **configuration.** Definitions of the six metrics derived from glacier quantities identified on
390 Kangjiaruo Glacier and neighboring Langtang Glacier (28.305°N, 85.702°E) are color coded to
391 the distributions of each metric for each RGI region. For each distribution, the black dot is the
392 median, the wide colored box outlined in black is 33-66% of the data and the thin colored bar
393 constrains the 10-90th percentile. Numbers in parenthesis are the number of glaciers within each
394 metric's distribution limited by each metric's derivation criteria (Methods Section 1.13). *Debris*
395 *expansion potential* measured from the present time (blue) will approach the distribution of
396 *future debris expansion* (black, plotted on the same line showing only the median and 10-90th
397 percentile) if debris cover can be assumed to continue to expand in a warming climate. **(a)** The
398 regional distribution and local abundance of the number of glaciers with an 'advanced' (>0.7)
399 *stage*. Langtang Glacier falls within this constraint.
400

401 **Fig. 5. Using current *stage* and *debris expansion potential* to anticipate the trajectory of**
402 **debris cover evolution.** *Debris expansion potential* passes through the origin, reaches a
403 maximum value (around 0.6) and converges to the true value of *future debris expansion* as *stage*
404 approaches 1. Our estimate of *future debris expansion* is plotted as an orange dot (median) and
405 bar (10-90th percentile). Black points and bars show a moving median and the 10-90th
406 percentiles, respectively. Regions with fewer glaciers had a wider moving median and moving
407 windows with <10 glaciers were skipped. The orange line is a spline fit to the moving median
408 values and forced through the metric constraints. Where $n > 500$ the points are colored to show
409 relative density. Percentages below each plot give the regional fraction of glaciers that meet the
410 criteria for metric derivation. The grey bar gives the range of the absolute value of latitude, or
411 distance from equator. Some seminal glaciers in debris cover research are shown along with the
412 four glaciers in Fig. 3.

413

414 **Fig. 6. Using current *stage* and *moraine abundance* to anticipate the trajectory of debris**
415 **cover evolution.** *Moraine abundance* follows a similar trajectory to *debris expansion potential*
416 but has no structural upper limit and converges to 1 as *stage* approaches 1. Regions with a lower
417 abundance of glaciers are shown in the Supplemental Information. Plot configuration is the same
418 as described in Fig. 5.

419

420 **1 Methods**

421 1.1 Satellite image selection

422

423 Landsat images were manually selected based on five criteria where relative significance is
424 ranked from 1 to 5:

- 425 1. Clouds (minimum coverage over glacierized areas)
- 426 2. Seasonal snow cover (minimum)
- 427 3. Time (most recent)
- 428 4. Sensor (newest, highest NASA assigned quality metric)
- 429 5. Abundance of glacierized area within an image (maximum)

430 The result of this selection process produced a 255 image library of Landsat satellite imagery
431 optimized for debris cover mapping at the most recent date possible (image library assembled in
432 2016) (Extended Data Fig. 1, Supplemental Information, Data S2). No images were used from
433 Landsat 7 after the Scan Line Corrector failure on 31 May 2003.

434 1.2 Glacier area cloud mask

435 While satellite images were selected on a minimum cloud cover criterion, some cloud cover
436 tolerance was necessary for images where no scene in the Landsat archive was entirely cloud
437 free. In order to include the portion of a scene that is cloud free while discarding the clouded
438 areas, a cloud mask was generated manually over glacierized areas for every satellite image.

439 1.3 Landsat composite without overlap

440 Within the set of Landsat satellite images selected for this study, there is considerable overlap
441 between neighboring images, especially towards the poles (Extended Data Fig. 1). If debris were
442 mapped for each image and merged into one regional or global debris map, the temporal
443 discontinuity between overlapping portions could cause one of two errors: (1) double counting
444 debris that has been translated perpendicular to glacier flow; or (2) incorrectly associate a map
445 date to a debris cover whose geometry has evolved. To avoid double counting and to assign the
446 correct map date to every debris shape, areas of overlap were removed in a 3-step automated
447 process:

448

- 449 1. **Remove sawtooth edges of Landsat 5 and Landsat 7 data.** Some edges of Landsat 5
450 and 7 images have a zone with a mix of data, no data and pixels with arbitrary values.

451 This zone would produce a complex seam if merged with a neighboring image. These
452 edge zones were automatically removed where present by computing an outward buffer
453 of the scene footprint perimeter by a distance equal to the width of the sawtooth zone,
454 buffering the result back by the same distance and clipping the image to this updated
455 shape.

456

457 2. **Preference to most recent image.** Where satellite image overlap exists, the more recent
458 image is given preference and the earlier date image is trimmed to share, but not cross, a
459 border with the later image. Before an image is trimmed, all possible neighbor images are
460 tested to optimize coverage with the most recent image. This was achieved by assigning
461 the image acquisition date to each image footprint in shapefile format and then iterating
462 through every image, locating neighbor images that have a nonzero intersection and
463 removing the overlap area from the image with the earliest acquisition date.

464

465 3. **Cloud mask holes filled.** Where the most recent scene is given preference from Step 2
466 but contains a no-data hole removed from the cloud mask (see above), the code attempts
467 to fill the hole with the next most recent underlying image if overlap exists at this
468 location. This was automated by iterating through neighbor images looking for older,
469 overlapping images that intersect the image specific cloud mask.

470 The result of this fully automated process is an overlap-free Landsat composite dataset with
471 preference to the most recently acquired satellite image and a clear data acquisition date assigned

472 to every location and subsequently every debris map shape generated from these data. Extended
473 Data Fig. 2 shows an example output of this process for Alaska.

474 1.4 1 km² minimum glacier area restriction for debris cover mapping

475 The minimum glacier area considered for debris mapping was 1 km². A substantial amount of
476 manual effort was conducted on an individual glacier basis for all regions on Earth. The
477 motivation for this area limit is that a consideration of glaciers smaller than 1 km² would have
478 been both time consuming and difficult to hold to a quality level consistent with bigger glaciers.
479 Glaciers with a surface area less than 1 km² sum to 39,583.2 km² or 8.2% of the RGI v6.0
480 excluding Greenland and Antarctica.

481 1.5 Translation error in RGI v6.0

482 Within the RGI v6.0 dataset, some translation errors were detected where glacier outlines
483 appeared to have a linear or nonlinear shift relative to Landsat imagery when projected in the
484 same (image specific UTM zone) coordinate system. Linear offsets were manually corrected and
485 nonlinear offsets were crudely corrected by shifting individual or clusters of glaciers, where a
486 glacier was the smallest element that was manipulated. No further alterations were made during
487 this step except the removal of glacier overlap to avoid topological errors and double counting of
488 glacier area. The two regions where translation errors were most present were 03 Arctic Canada
489 North and 04 Arctic Canada South where a high latitude amplification of geolocation errors from
490 variable projections used during mapping efforts is a probable cause. Considering the sum of
491 false positive (FP) and false negative (FN) errors introduced by shifted glacier outlines, the error
492 for these two regions are 4434.3 km² (4.4% of the region) and 71.3 km² (0.2%), respectively.

493 Because translation error is not directly related to specific glacier shapes, these values were not
494 included in the total RGI errors presented in Table S2.

495 1.6 Initial debris cover map

496 With each satellite image trimmed to a geometry that fits seamlessly with its neighbors
497 (Extended Data Fig. 1, 2), an initial, first iteration debris map was generated. Debris cover was
498 mapped following a well-established method¹⁸⁻²⁰ where: 1. off glacier area was removed from
499 the raw near-infrared (NIR) and Short-wave infrared (SWIR) bands for each satellite image; 2.
500 the band ratio NIR/SWIR was computed; and 3. a pixel-based threshold value discriminating
501 between debris-covered and debris-free glacier area was applied. While the optimum threshold
502 value for mapping debris cover will vary between satellite images²⁰, only one threshold value,
503 1.57 (a value found optimal for a Landsat 8 image in Northern Pakistan by (ref. ³)), was used
504 across all scenes and all three Landsat sensors used. Results using a single threshold value was
505 deemed satisfactory for the scope and scale of this project (Supplemental Information) and is
506 consistent with other large-scale debris mapping studies^{18,37,38}. This initial, global-scale debris
507 map provided the basis for the identification and removal of false positive (FP) errors both in the
508 debris map as well as in the RGI v6.0.

509 1.7 FP errors in the initial debris cover map and the RGI

510 While the output of the initial debris cover map identified debris-covered portions of Earth's
511 glaciers, it also classifies bedrock nunataks, non-glacierized land and heavily shaded areas
512 (lightly shaded regions should be mitigated by the band ratio) as debris cover. Depending on the
513 quality of the glacier outlines and the sun angle during the time of satellite image acquisition

514 coupled with the amplitude of the surrounding topography, these errors can be substantial. To
515 both quantify and remove these errors a series of manual identification steps were conducted.

516 The geometry of a nunatak or non-glacierized feature located within a glacier shape is accurately
517 defined in the initial debris map. By on-screen, visual inspection against the Landsat composite
518 imagery, a decision was made whether each shape in the initial debris map was true positive (TP)
519 or FP debris cover. This decision was logged by drawing a wider shape, or lasso, around all FP
520 area. This was done for all glaciers on Earth in a manually intensive effort by one person (S.
521 Herreid) for consistency. For the second iteration debris map, area that fell within a FP lasso was
522 not considered part of the glacier domain while area outside of the FP lasso was again mapped as
523 TP debris-covered glacier area (Extended Data Fig. 3).

524 1.8 False negative errors added to the RGI v6.0

525 Since the RGI v6.0 is a composite dataset of automated routines, semi-automated routines and
526 manual glacier digitization by many individuals²¹ with a variable definition of what a glacier is
527 and variable expertise (both human and algorithm) in including debris-covered termini, there are
528 instances where substantial portions of a glacier are excluded from the inventory. Additionally,
529 real glacier area changes can be substantial over very short time intervals and frontal positions
530 can evolve on the order of kilometers between the source data used to produce the RGI and the
531 Landsat composite used in this study.

532 While many ambiguities cloud the definition of a glacier and the boundary defining a debris-
533 covered terminus, wider glaciological conclusions built upon sharp boundaries drawn within
534 these ambiguities are aided by consistency. Subjectivity in manual differentiation is unavoidable,

535 particularly for debris-covered areas³⁹, but by having only one person manually assess and alter
536 the entire RGI, the final refined result is likely to be a more consistent product.

537 To incorporate RGI false negative (FN) glacier area present in the Landsat satellite composite
538 dataset, missing areas were manually digitized (red outlined shapes in Extended Data Fig. 3). FN
539 area added was not exclusively debris-covered and thus required a second debris cover
540 classification iteration using the updated glacier area as input.

541 1.9 Shaded area causing FP debris to be mapped in TP bare ice area

542 Areas mapped as debris in the initial debris map that were in reality optically dark, bare glacier
543 ice due to shading were manually identified similar to the treatment of FP errors. The shaded
544 error, however, were only removed from the debris cover results and the intersecting RGI area
545 was left intact. For locations where a cast shadow confused the automated debris mapping
546 algorithm but a distinction could be made visually, the identifying shape was manually drawn to
547 preserve the debris structure, thus removing only the bare ice portion of the shaded area from the
548 debris map. The area of FP debris mapped in TP bare ice area is ephemeral and not intrinsic to
549 any derived dataset, yet we include the total shadow area removed in Extended Data Table 2 to
550 document the magnitude of this factor.

551 1.10 Exclusion of Antarctica and unique considerations for Greenland

552 Antarctica, where debris cover is anticipated to be sparse, was excluded from this study, while
553 debris cover observed in Greenland prompted the inclusion of the entire Greenland ice sheet,
554 beyond the RGI's inclusion of only periphery glaciers. RGI v6.0 Greenland Periphery glacier
555 outlines were given preference to, and merged with Greenland ice sheet outlines from⁴⁰. Due to
556 incongruities of this merged product and the exceptionally large size of this region, a simplified

557 approach to removing glacier outline error was used for Greenland to speed up the derivation of
558 a debris cover map. Rather than identifying errors (e.g. method shown in Extended Data Fig. 3),
559 TP debris area was identified manually. Debris shapes outside of those manually identified as TP
560 were not removed or differentiated between FP area, area in shadow, clouded area and networks
561 of surface ponds. This approach allowed the quality of the debris maps to be equal to those of the
562 other RGI regions on Earth but disabled the ability to quantify ice outline errors.

563 1.11 Final debris map with a refined version of the RGI

564 With all of the FP error area removed and FN error area added, an updated and refined version of
565 the RGI (termed ‘SamRGI’ for clarity) was produced and used as input for a final iteration of the
566 debris mapping algorithm. While the debris maps were generated for each (trimmed) Landsat
567 scene separately in the image specific UTM zone, the final regional debris maps were merged
568 and projected into a set of continental scale map projections selected to offer accurate area
569 calculations (Supplemental Information).

570 1.12 Fraction of RGI v6.0 and SamRGI considered

571 The fraction of RGI v6.0 considered is defined as the ratio of the following two quantities:

572 • Unaltered RGI v6.0 regional area with glaciers $<1 \text{ km}^2$ removed and area that does not
573 intersect the Landsat image composite removed.

574

575 • unaltered RGI v6.0 regional area.

576

577 This provides an estimate of the fraction of all glaciers, including those with a surface area <1
578 km², that are considered in this study. The value is not penalized for FP area that is later removed
579 to improve the RGI.

580 The fraction of SamRGI considered does not penalize for glacier <1 km² being removed and
581 includes all of the glacier geometry edits made in this study. It is defined as the ratio of:

- 582 • Altered RGI v6.0 regional area with glaciers <1 km² removed and area that does not
583 intersect the Landsat image composite removed.
- 584
- 585 • Altered RGI v6.0 regional area with glaciers <1 km² removed both inside and outside of
586 the Landsat image composite.

587 1.13 Criteria for computing the debris cover metrics

588 The criteria for metric computation varied per metric and was most restrictive for metrics that
589 depend on estimates of the equilibrium line.

- 590 • **2 km² minimum glacier area** For the computation of all metrics (*AAR, stage, debris*
591 *expansion potential, future expansion potential, percent debris-covered* and *moraine*
592 *abundance*), glaciers with a surface area less than 2 km² were excluded. This was done to
593 statistically increase the TP rate of the debris maps. Larger glaciers have a larger capacity
594 for debris coverage and more debris pixels increases the probability of a high TP debris
595 classification rate.
- 596 • **Minimum 7% debris-covered unless debris-covered area is greater than 10 km²** For
597 glaciers where *percent debris-covered* was less than 7%, computations of *AAR, stage,*

598 *future expansion potential* and *moraine abundance* were discarded (metric values set to -
599 9999). This limit was selected in an attempt to only consider glaciers where there was a
600 higher probability that the debris extent extended close to the true equilibrium line
601 (Supplemental Information) while also being as low of a value as possible to maximize
602 inclusivity. This limit was discarded in cases where a glacier's summed debris-covered
603 area was 10 km² or greater to include large glaciers with a likely developed and
604 confidently mapped debris cover, but a debris-covered percentage falling below the 7%
605 threshold.

606 • **A non-existent debris cover cannot “expand”** Where *debris expansion potential* was
607 measured to be 0 (in a case of no mapped debris cover) the metric value was set to -9999
608 indicating that the potential of a debris cover to expand is unknown/not applicable.

609 • ***Future expansion potential cannot be negative*** *Future expansion potential* was set to -
610 9999 where it was computed as a negative value.

611 1.14 Equilibrium line estimate from debris exposure

612 Debris cover that is exposed at the surface of a glacier for longer than one year is, by definition,
613 located within the ablation zone. Debris that is exposed at the surface of a glacier for less than
614 one year while remaining an element of the glacier for more than one year is, by definition,
615 located within the accumulation zone. Drawing on these two axioms and one fundamental
616 assumption, debris cover can be used to define an equilibrium line estimate. The assumption is
617 that a glacier with a sufficient debris-covered area (defined here as glaciers with 7% debris cover
618 and/or >10 km² of debris-covered area) will have (at least some) debris inputs above the
619 equilibrium line and some of that debris will be exhumed to the surface at, or near (below), the

620 equilibrium line. If the top, up-glacier extent of a debris cover can be expanded orthogonal to
621 glacier flow to the full glacier width and shifted up-glacier to correct for the englacial flow path
622 of debris that is not deposited onto the glacier exactly at the equilibrium line, an equilibrium line
623 estimate can be defined (Extended Data Fig. 4).

624 To transform mapped debris geometry (which can be any shape, e.g. medial moraine bands,
625 lateral moraines or complete coverage of the glacier width) to a top of the debris coverage line
626 that spans the full glacier width, a buffer function was applied. In the cases of several medial
627 moraine bands or complete debris coverage, the process is more simplistic: an outward extension
628 of the debris shapes a short distance will overlap/merge to form a synthetically debris filled
629 ablation zone. In the most difficult case, where there is one narrow lateral moraine on only one
630 side of a glacier, the buffer distance will need to extend the full width of the glacier to achieve
631 the same, desired, synthetically full ablation zone. Following this logic, a buffer-out distance that
632 is appropriate for a small glacier will be insufficient for a large glacier and a buffer-out distance
633 for a large glacier will be excessive for a small glacier. To account for both this size variability
634 and the case of only one lateral moraine, we use the readily known quantity glacier area to
635 roughly estimate glacier width (Supplemental Information) which we set as our buffer-out
636 distance, d_{out} . After generating a synthetically full debris-covered ablation zone with d_{out} , the
637 ablation zone shape is buffered back inward a distance d_{in} . Following the guiding hypothesis that
638 a sufficiently debris-covered glacier will have mappable debris located near the ablation zone
639 (Supplemental Information), we correct for an anticipated swath of bare glacier ice that separates
640 the first mappable debris cover and the true equilibrium line by a distance d (Extended Data Fig.
641 4). This correction is made by the relation $d_{in} = xd_{out}$ where x is a defined coefficient between 0
642 and 1 that enables an estimate of d , where $d = (1-x)glacier\ width$.

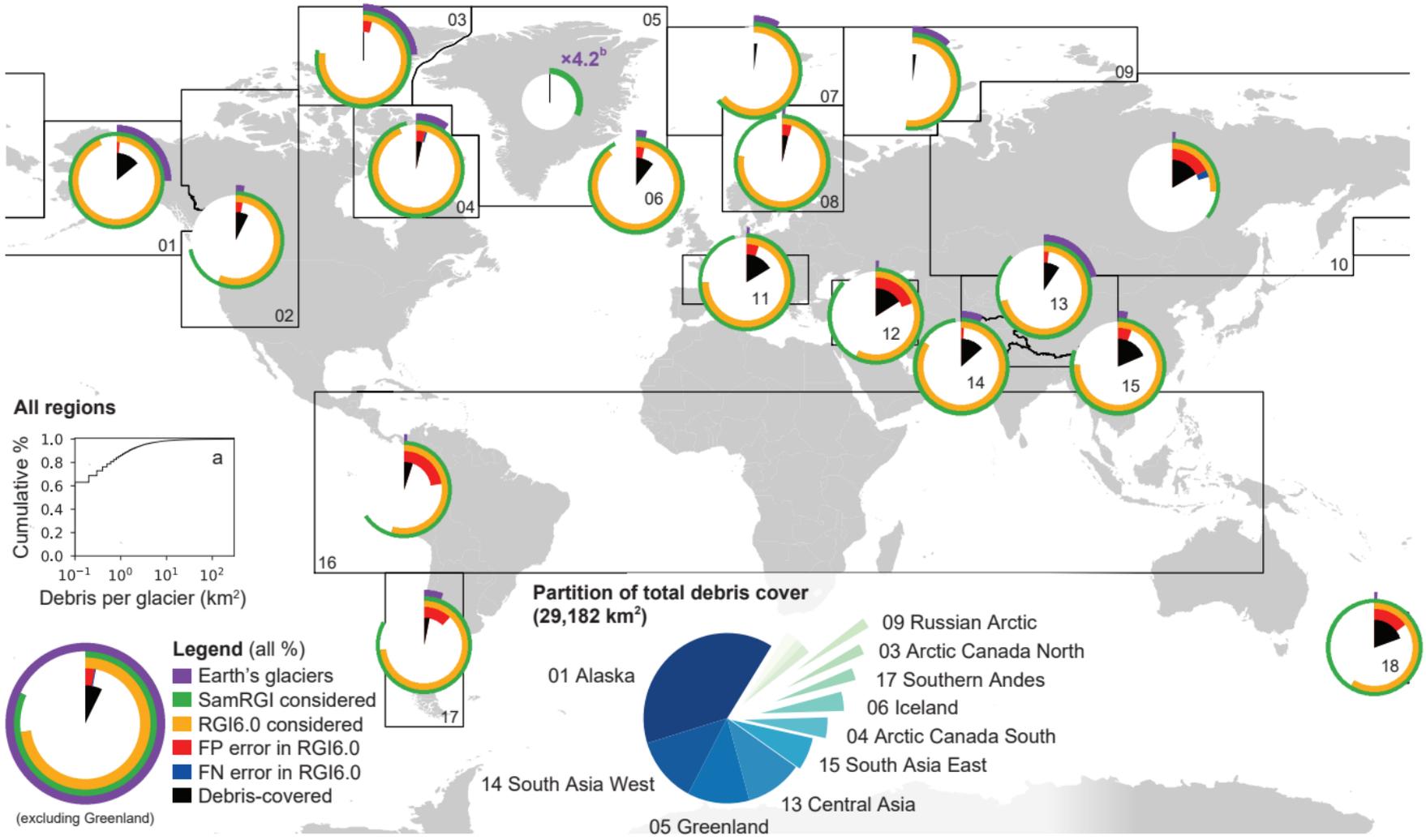
643 Using $x = 0.75$ (Supplemental Information) and estimated glacier widths, an ablation zone was
644 derived for every glacier on Earth with a surface area $>2 \text{ km}^2$. Glaciers that did not meet the 7%
645 debris cover and/or $>10 \text{ km}^2$ debris-covered area criteria were deemed unlikely to have sufficient
646 debris cover to successfully define an ablation zone and were excluded from further analysis.

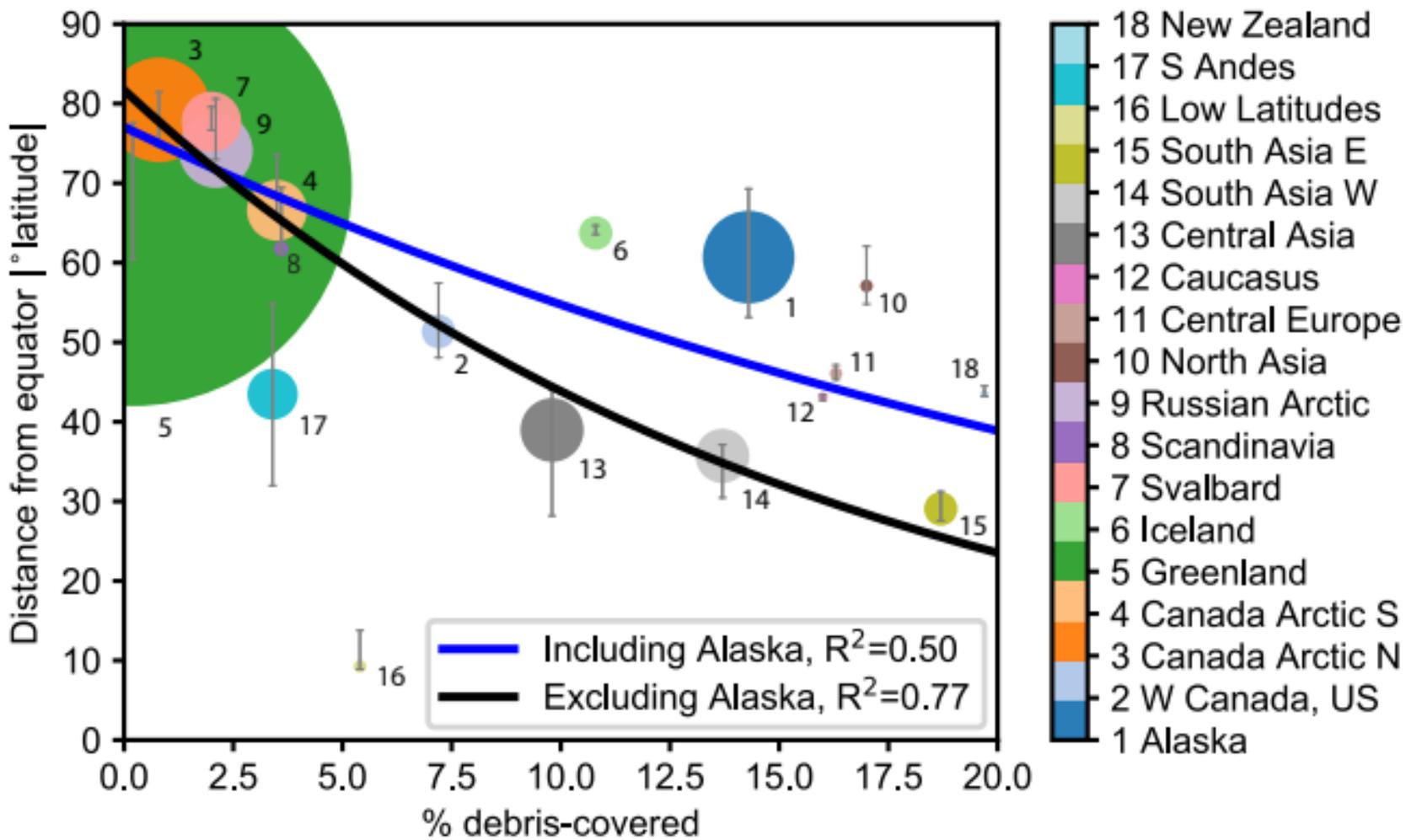
647

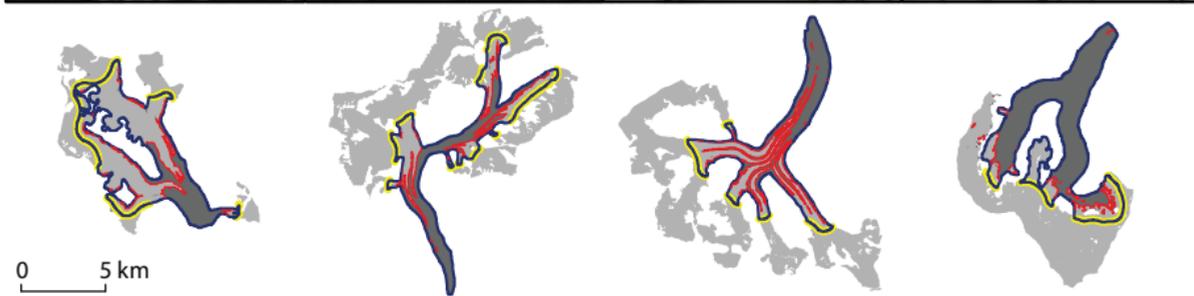
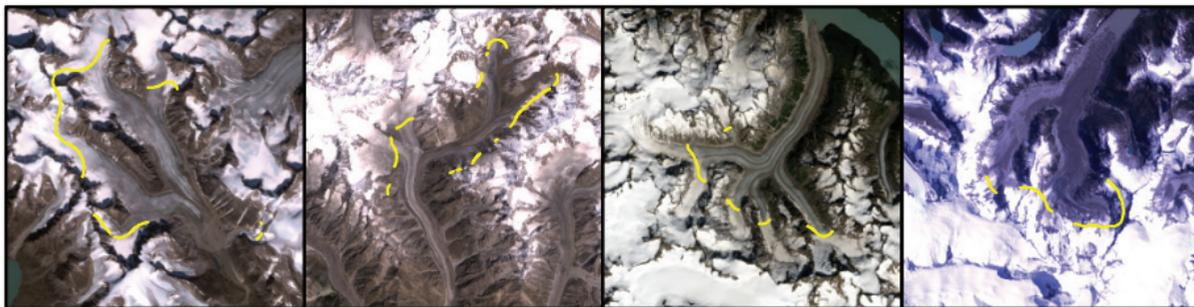
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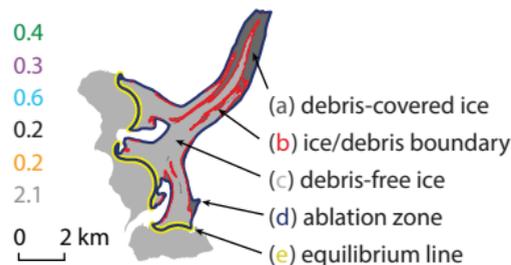
658







Ayunnamat Gl. (46 km ²) Canadian Arctic South 66.493°N, 64.599°W 0.3 0.3 0.5 0.2 0.2 1.2	Ghandogoro Gl. (66 km ²) South Asia West 35.622°N, 76.400°E 0.7 0.5 0.6 0.2 0.2 2.0	Konamoxl Gl. (66 km ²) Alaska/British Columbia 59.296°N, 137.696°W 0.6 0.5 0.7 0.1 0.2 3.1	Grosse Gl. (65 km ²) Southern Andes 46.534°S, 73.358°W 0.5 0.7 0.4 0.1 0.4 1.4
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AAR
 $((a+c)-d)/(a+c)$

Stage
 a/d

Debris expansion potential
 $b/\text{perimeter}(a)$

Future debris expansion
 $e/\text{perimeter}(d)$

Percent debris-covered
 $a/(a+c)$

Moraine abundance
 $\text{perimeter}(a)/\text{perimeter}(d)$

