

Vanishing Small Glaciers in the Cordillera Real, Bolivia (1998-2024)

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1. Comparison Between Glaciers in RGI 7.0 and the A&M26 Inventory for 1998

The glacierized area in version 7.0 of the Randolph Glacier Inventory (RGI 7.0) and the 1998 inventory from Adrianzen and Malone (2026), hereafter A&M26, are similar, with most differences due to uncertainty in the area measurements. The glacierized area in the RGI 7.0 is 6.64 km² smaller than the central area estimate of the A&M26 inventory, but it falls within its 2- σ uncertainty interval (Table 1). Also, the extents of individual glaciers in the two inventories largely overlap (Fig. S1, Fig. S2). Of the 485 glaciers found in both inventories, only 31 glaciers are larger in the A&M26 inventory than in the RGI 7.0 by an amount that exceeds the 2- σ uncertainty in the area measurements. In the A&M26 inventory, 8 are smaller than in the RGI 7.0 by a statistically resolvable amount, which reduces the additional area by 0.69 km². The 446 glaciers that do not have statistically resolvable differences in their areas, by contrast, contribute 3.46 km² of additional area to the A&M26 inventory, with 294 of them being larger in the A&M26 inventory. Thus, over half (52.1%) of the additional area in the A&M26 inventory for 1998 is attributed to glaciers whose areas in the two inventories are not statistically different.

The A&M26 inventory for 1998, however, differs notably from the RGI 7.0 in terms of how many individual glaciers it contains (Table 1). It contains 82 glaciers in 1998 that are not found in the RGI 7.0 (Fig. S1, Fig. S2). These glaciers contribute 1.57 ± 0.14 km² of glacierized area to the A&M26 inventory not found in the RGI 7.0. In addition, two glaciers in the RGI 7.0 are represented by multiple glacier basins in the A&M26 inventory. One RGI 7.0 glacier (RGI2000-v7.0-G-16-03355) is represented by three glaciers in the A&M26 inventory. Another (RGI2000-v7.0-G-16-03269) is represented by two glaciers. Lastly, two glaciers in the RGI 7.0 (RGI2000-v7.0-G-16-03094, RGI2000-v7.0-G-16-03498) are not included in the A&M26 inventory as they are part of larger glacier basins in the A&M26 inventory. In total, there are 83 additional glacier basins in the A&M26 inventory than in the RGI 7.0.

Table S1. Number (area [km²]) of glaciers in version 7.0 of the Randolph Glacier Inventory (RGI 7.0) and number (area [km²] $\pm$ uncertainty [km²]) of glaciers in the A&M26 inventory analyzed in this study for 1998

–	RGI 7.0	A&M26, 1998
Small, Low-Lying Glaciers	236 (25.78)	286 (25.66 $\pm$ 0.64)
Small Glaciers	390 (50.27)	467 (53.39 $\pm$ 0.94)
All Glaciers	487 (207.32)	570 (213.96 $\pm$ 7.93)

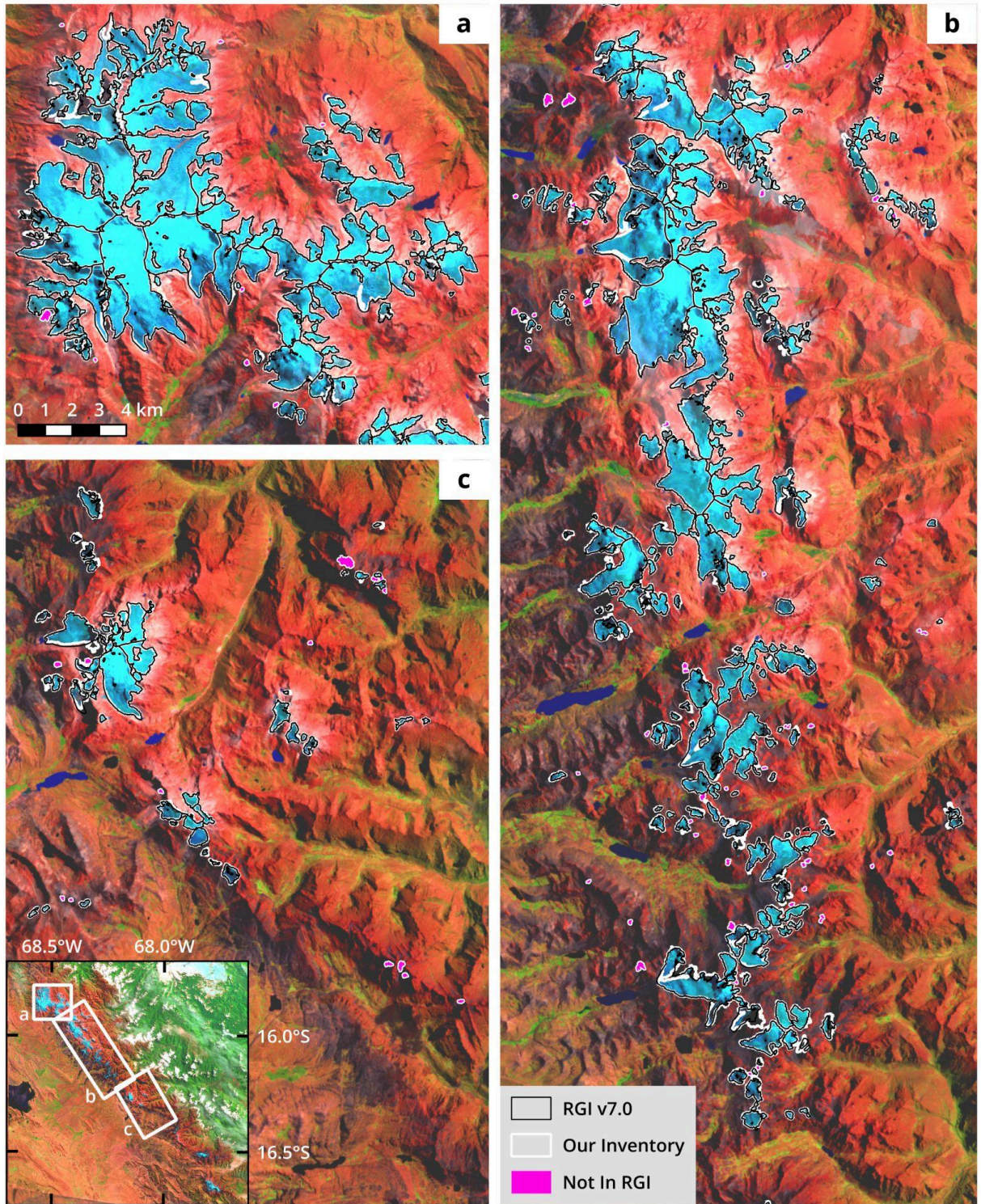


Fig. S1. Comparison of glacier extents in the RGI 7.0 and the A&M26 inventory for 1998, noting glaciers in the A&M26 inventory not found in the RGI 7.0. The background map is the Landsat composite image from 1998, used to construct the A&M26 inventory for 1998.

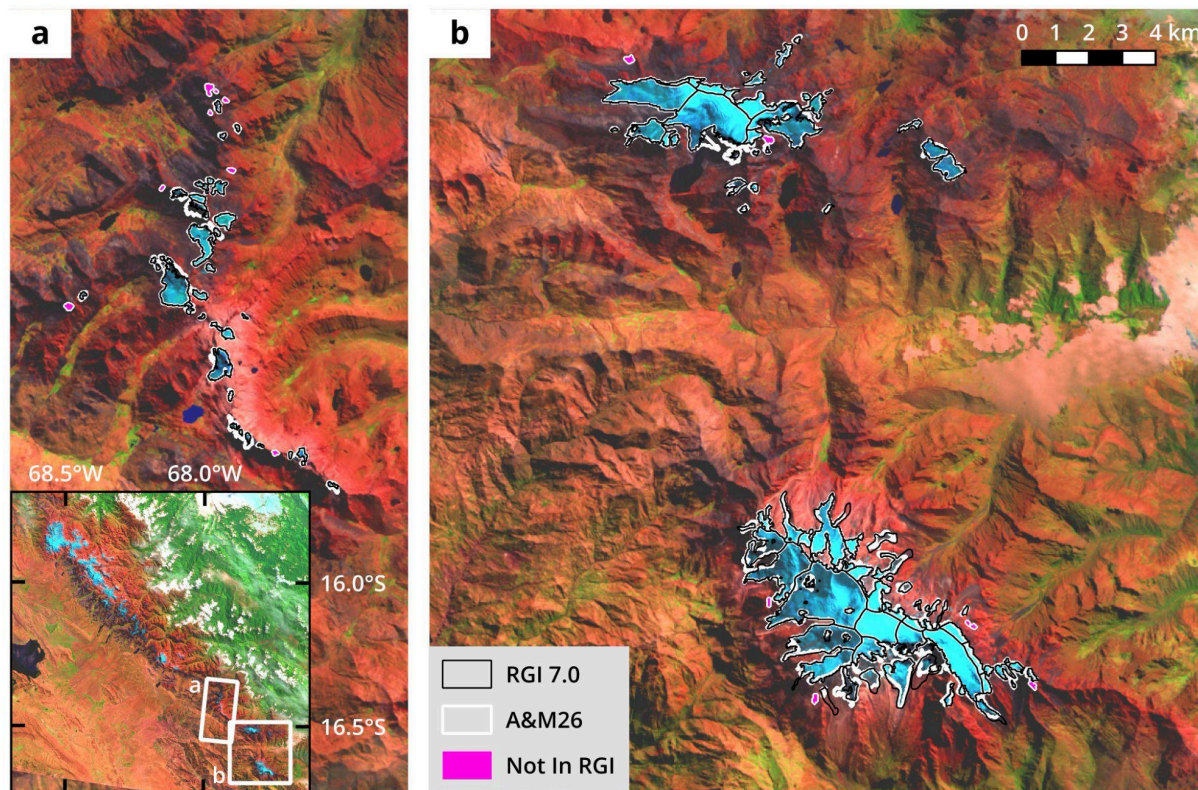


Fig. S2. Same as Fig. S1 but for glaciated regions further south in the Cordillera Real.

2. Characteristics of Glaciers Found in A&M26 Inventory But Not Found in the RGI 7.0

The glaciers in the A&M26 inventory that are not also found in the RGI 7.0 have a preference for their size, elevation, and aspect (Fig. 3S). All were small ($<0.5 \text{ km}^2$). The largest of these glaciers not included in the RGI 7.0 had an area of 0.1422 km^2 . Most (87.8%) were low-lying (maximum elevation $<5400 \text{ m}$). Nearly all (89.0%) faced southward (i.e., aspect of south, southeast, or southwest). This aspect tendency likely reflects the remote sensing scene selection used to construct the inventories. Landsat scenes in this region have a northeast azimuth, leaving southward-facing slopes often shadowed. The single Landsat scene used to construct the RGI 7.0 is from the austral winter (13 June 1998) when the sun is lower in the sky than in the composite scenes. The Sun Elevation in the 13 June 1998 scene is 38.15° . It is 44.31° in the 1998 composite, which includes one scene from the middle of September. Thus, more of the southward-facing slopes were shadowed in the Landsat scene used to construct the RGI 7.0, obscuring some glaciers that could be detected in the composites.

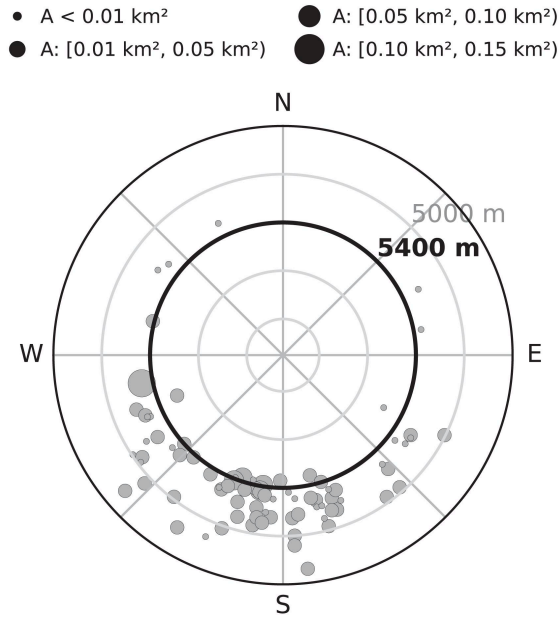


Fig. S3. Area (dot size), maximum elevation (distance from center), and mean aspect (angle) of the 82 glaciers found in the A&M26 inventory for 1998 but not found in the RGI 7.0. Lower elevations are toward the outside. The cutoff elevation for low-lying glaciers (5400 m) is bolded.

3. Rates Of Glacierized Area Loss By Glacier Size

The rate of glacierized area loss depends on both the size of the glacier and the amount of glacierized area in each size bin, while the rate of relative loss rate depends mainly on the size (Table S2). The highest rates of glacierized area loss were for glaciers with size bins in 1998 of between 0.1 to 0.5 km² and 1.0 to 5.0 km². These size bins, however, also contained the most glacierized area in 1998: 19.9% of the glacierized area for the 0.1 to 0.5 km² bin and 43.5% for the 1.0 to 5.0 km² bin. In terms of loss rates relative to the glacierized area in each bin, this relative loss rate monotonically decreases as the size of the glaciers increases. The relative loss rate of the bin for the smallest glaciers (<0.1 km²) is about double to triple the rate for the bin with the most glacierized area (1.0 to 5.0 km²). It is amplified by a factor of about three to eight compared to the bin with the largest glaciers (>5.0 km²).

Table S2. Rate of Area Change [km² y⁻¹] ± Uncertainty [km² y⁻¹] (Rate of Area Change Relative to 1998 area [% y⁻¹] ± Uncertainty [% y⁻¹]) Based on Their Size in 1998

Size In 1998	1998 to 2010	2010 to 2024	1998 to 2024
<0.1 km ²	-0.48 ± 0.04 (-4.4 ± 0.4)	-0.20 ± 0.02 (-1.8 ± 0.2)	-0.33 ± 0.02 (-3.0 ± 0.2)
0.1 to 0.5 km ²	-1.17 ± 0.09 (-2.8 ± 0.2)	-0.73 ± 0.06 (-1.7 ± 0.2)	-0.93 ± 0.04 (-2.2 ± 0.1)
0.5 to 1.0 km ²	-0.57 ± 0.09 (-1.5 ± 0.2)	-0.41 ± 0.07 (-1.1 ± 0.2)	-0.48 ± 0.05 (-1.3 ± 0.1)
1.0 to 5.0 km ²	-0.68 ± 0.18 (-0.9 ± 0.2)	-0.78 ± 0.14 (-0.8 ± 0.2)	-0.82 ± 0.08 (-0.9 ± 0.1)
>5.0 km ²	-0.16 ± 0.10 (-0.5 ± 0.3)	-0.17 ± 0.08 (-0.6 ± 0.3)	-0.17 ± 0.05 (-0.5 ± 0.2)

4. Explanation of the Variables in the Supplementary CSV File and Shapefile

Table S3. Name and Units For Variables In the Supplementary CSV File and Shapefile

Column Name	Long Name	Unit
glacier_id	glacier identification number	–
rgi_id	glacier identification number in the RGI 7.0	–
rgi_reg1	first-order region number in the RGI 7.0	–
rgi_reg2	second-order region number in the RGI 7.0	–
glims_id	glacier identification number in GLIMS database	
cenlon	centroid longitude of each glacier's extent in 1998	degrees
cenlat	centroid latitude of each glacier's extent in 1998	degrees
zmin_m	minimum elevation of each glacier's extent in 1998	meters a.s.l.
zmax_m	maximum elevation of each glacier's extent in 1998	meters a.s.l.
zmed_m	median elevation of each glacier's extent in 1998	meters a.s.l.
zmean_m	mean elevation of each glacier's extent in 1998	meters a.s.l.
slope_deg	mean slope of each glacier's extent in 1998	degrees
aspect_deg	mean aspect of each glacier's extent in 1998	degrees
aspect_dir	mean aspect of each glacier's extent in 1998	compass direction
1998_count	number of glacerized areas in 1998 within each glacier's extent in 1998	number of glaciers
1998_A_km2	area of glacerized areas in 1998 within each glacier's extent in 1998	km ²
1998_U_km2	uncertainty of glacerized areas in 1998 within each glacier's extent in 1998	km ²
2010_count	number of glacerized areas in 2010 within each glacier's extent in 1998	number of glaciers
2010_A_km2	area of glacerized areas in 2010 within each glacier's extent in 1998	km ²
2010_U_km2	uncertainty of glacerized areas in 2010 within each glacier's extent in 1998	km ²

References

Adrianzen G and Malone AGO (2026). Constraining the Trajectory of Glacier Loss in the Cordillera Real (Bolivia) via a Time-Evolving Inventory. *Remote Sensing*, **18**(6) 905. (doi: <https://doi.org/10.3390/rs18060905>)

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