Supplement:

Unprecedented Twenty-First Century Glacier Loss on Mt. Hood, Oregon, U.S.A.

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This supplement contains detailed descriptions and repeat photographs of the glacier changes on Mt. Hood between 2003 and 2023 (Fig. S1) as well as a list of satellite images used for mapping glacier extent from 2020 to 2023. The descriptions and photographs of the glaciers move counterclockwise around the mountain, beginning with the Zigzag Glacier and detouring vertically once to capture the Coalman Glacier (Fig. S1). All volcanic age and rock descriptions come from the U.S. Geological Survey Eruption History of Mount Hood, Oregon website (U.S.G.S., 2023, https://www.usgs.gov/volcanoes/mount-hood/science/eruption-history-mount-hood-oregon): the Main Stage eruptions occurred >660-30 ka (ka = kilo annum; mostly basaltic >500 ka; mostly andesitic <500 ka), the Polallie 30-12 ka (dacite and pyroclastic flows), the Timberline ~1.5 ka (dacite and pyroclastic flows), and the Old Maid 1781 C.E. and shortly thereafter (pyroclastic flows and lahars). The glacier areas noted for 2015 or 2016 are from Fountain et al. (2023). The supplement also contains Tables S1 and S2.

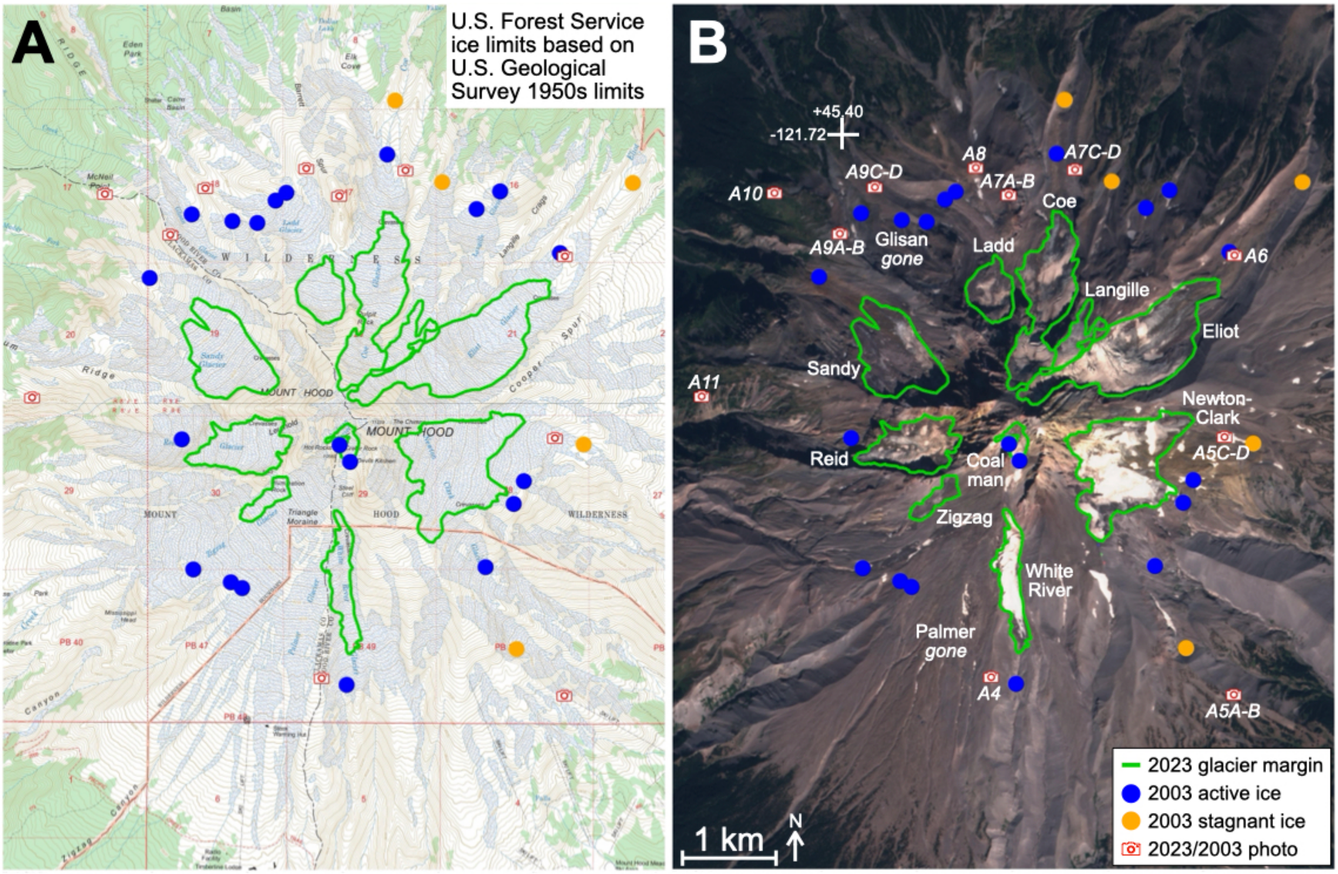

Figure S1: U.S. Forest Service 2016 topographic map of Mt. Hood (A) and 19 September 2023 Sentinel-2 image of the same region (B). Green lines are September 2023 outlines of remaining active glaciers. Blue symbols are the lowest observed actively flowing glacial ice in September 2003 while orange symbols are the lowest elevations of stagnant ice observed in September 2003. Red camera symbols denote repeat photography locations with Fig. S4-S11 with identifications noted on right.

Zigzag Glacier (Fig. S2) has a southwest aspect with its accumulation area between two rock walls that are volcanic bedrock erupted >100 ka. Conversely, the pyroclastic flows from the 1781 eruption of Mt. Hood created a wide featureless surface onto which the glacier flows in its ablation area. This broad south-facing surface means Zigzag's terminus is directly exposed to solar radiation. In 2003, there was minimal debris cover on Zigzag and crevasses were visible in the accumulation area. The terminus spread broadly across the pyroclastic flows to a subtle moraine and extended down to ~2350 m asl. By 2023, Zigzag's active terminus had risen in elevation by ~250 m to ~2600 m asl. The glacier had split into three bodies of ice, all heavily or entirely debris covered. The uppermost, northernmost, and largest body of ice exhibited still-active crevassing. The two lower bodies exhibited no actively maintained crevasses, implying stagnation. Other parts of Zigzag noted in 2003 had transitioned to stagnant ice or disappeared. The glacier's area of active ice was mapped in 2015 at 0.168±0.005 km^2, and at 0.101±0.007 km^2 in 2023, a loss of ~40% in just eight years. Two other separate perennial snowfields/stagnant ice regions had areas of 0.153±0.046 km^2 and 0.030±0.009 km^2 in 2015; in 2023 the former had barely any snow cover while the latter was not visible.

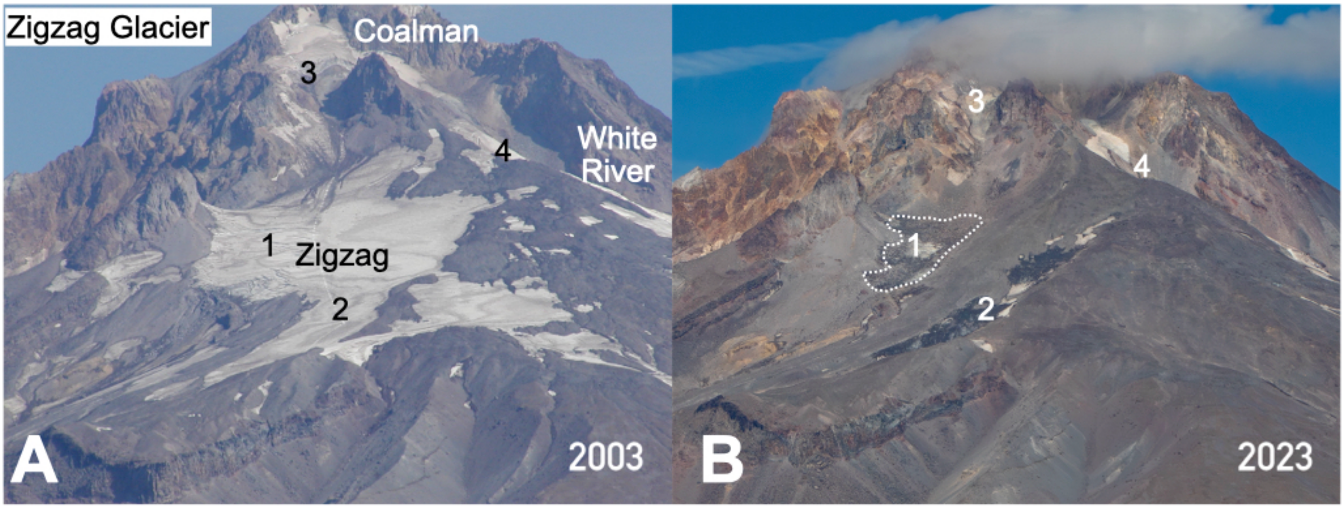

Figure S2: Zigzag Glacier from across the valley (shot location 45.29275º, -121.80044º) repeat photograph from 2003 (A) and 2023 (B). 1. Denotes the reduction in area of Zigzag Glacier to its 2023 limit (dashed white line in B). 2. Remnant stagnant ice that once was part of the actively flowing glacier. 3. Western terminus of Coalman Glacier that has retreated but is still visible in 2023. 4. Top of White River Glacier that has separated more fully from the eastern terminus of Coalman Glacier since 2003.

Palmer Glacier was first identified as a glacier in 1924, flowing on the same pyroclastic apron as Zigzag Glacier (Nelson, 1924). It was still an active glacier in 1981 as its maximum ice thickness reached ~60 m (Driedger and Kennard, 1986). As of 2003, it was no longer an active glacier, only a perennial snowfield over stagnant ice without crevasses or evidence of fine glacial sediment suspended in the meltwater stream. Fountain et al. (2023) mapped Palmer as two perennial snowfields in 2015/2016 at 0.077±0.023 km^2 and 0.019±0.006 km^2. By 2023, this snowfield was seasonal, disappearing in late September to October despite efforts by Timberline Lodge Ski Area to farm and store snow for summer ski operations. Once this snowfield melts in late summer, small stagnant ice from the once-active glacier remains under rock debris and ski-area-related trash.

Coalman Glacier (Fig. S3) is south facing, occupies a collapsed lava dome (erupted ~1.5 ka), and is bounded by cliffs to the east (erupted 12-30 ka) and west (erupted >100 ka). Coalman's flow is split by a rock promontory into two lobes: one descending to the southwest towards Zigzag Glacier (Fig. S2) and the other descending to the southeast towards White River Glacier (Fig. S2, S3A, B). Large fumaroles formed in the late 1800s around the rock promontory, Crater Rock, and both are active to this day, likely influencing the glacier (Lillquist and Walker, 2006). Indeed, Coalman was part of the accumulation area of White River and Zigzag glaciers in the 1800s, separating from White River Glacier by 1912 (Lillquist and Walker, 2006) and later from Zigzag Glacier (unknown timing but it was separate by 2003 based on our mapping that agrees with Fountain et al. (2023)). Its accumulation area extended to the summit of Mt. Hood until the late 1990s. In 2003, the western lobe flowed down to ~3190 m asl while the eastern lobe reached ~3130 m asl, terminating in a lake near a fumarole (Fig. S3A, B). By September 2021, our last visit to the summit when photography was possible, what remained was an isolated ice mass resting on the steep slope of the ridge to the west; the highest remaining accumulation area on a well-buttressed slope reduced to dark firn with debris along the edges and old crevasses filling with debris; a single tiny patch of dead ice on the large gentlysloped summit area (Fig. S3C, D); and a thinning area of active ice just above the aforementioned lake to the east (Fig. S3B). In 2023, repeat photography of the glacier was not possible due to cloud cover. The glacier's eastern terminus had no significant change in elevation while the western terminus had risen ~40 m to ~3230 m asl. Coalman's area was mapped at 0.099±0.001 km^2 in 2016 and at 0.057±0.004 km^2 in 2023, a loss of ~42% in just seven years. Much of this area loss occurred along the western lobe that is exposed to more direct solar radiation than the eastern lobe.

Figure S3: Photographs of Coalman Glacier from 2003 (A) and 2021 (B-D). A-B. The eastern lobe terminus (1) in 2003 (A) and in 2021 (B). C. Remnant ice (2) in 2021 in what had been the highest part of the accumulation area. D. Stagnant ice (3) in 2021 in the former accumulation area of the western lobe.

White River Glacier (Fig. S4) faces due south so the entire glacier receives direct solar radiation. Prior to 1912, White River and Coalman glaciers were connected (Lillquist and Walker, 2006). Since then, the glacier's accumulation area has begun below a fumarole and flows between pyroclastic flows to the west and a rock cliff to the east. In 2003, the glacier descended to an elevation of ~2130 m asl, with debris cover on the lowest 100 m of the terminus. The terminus rose in elevation by ~110 m to ~2240 m asl in the last 20 years. As of 2023, the glacier had thinned significantly and lost most large crevasses near its terminus, yet it had maintained similar debris coverage. Large crevasses also remained in the accumulation area above. In 2015, the glacier's area was mapped at 0.287±0.046 km^2, and in 2023 at 0.271±0.019 km^2, a loss of ~6% in eight years. In 2015, a separate perennial snowfield/stagnant ice region had an area of 0.048±0.014 km^2; in 2023 this field had shrunk.

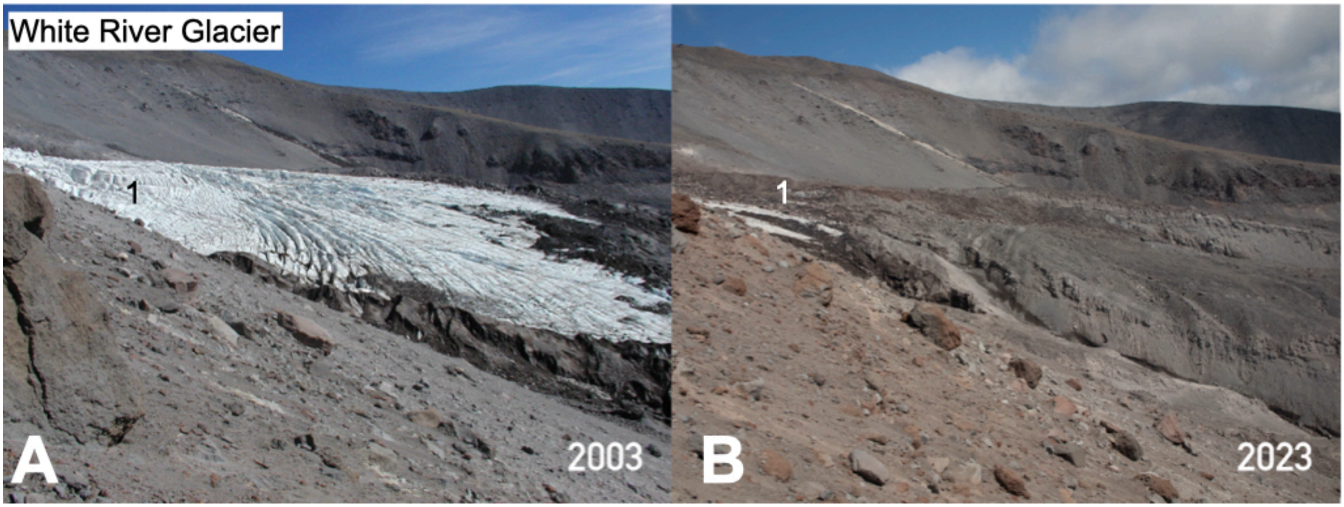

Figure S4: White River Glacier terminus from 2003 (A) and 2023 (B) (shot location 45.34912º, -121.70219º). 1. Note the retreat of the terminus.

Newton-Clark Glacier (Fig. S5) faces east with a broad accumulation area. The glacier flows into two drainages: Clark to the southeast (Fig. S5A, B) and Newton to the east (Fig. S5C, D), with the former having greater exposure to direct solar radiation. The 2003 terminus in the Clark drainage reached ~2320 m asl while the margin in the Newton drainage extended to ~2420 m asl. Debris cover on the terminus was moderate, except in the area of a recent landslide onto the glacier from the headwall (Fig. S5C). In 2023, extensive debris coated the Newton-Clark Glacier terminus in the Newton drainage. We observed a landslide onto the glacier while field mapping, with additional rockfall occurring every 5 to 10 minutes. The new landslide covered a large portion of the northern uppermost area of the glacier and added to the significant debris coverage that dominates most of the glacier's surface. In the last 20 years, the active ice margin in the Clark drainage rose by ~300 m to ~2620 m asl, with only stagnant ice remaining. The southeast active ice margin was now on the ice divide between the two drainages. The terminus in the Newton drainage rose by ~60 m to ~2580 m asl. Newton-Clark's active ice area was mapped at 1.134±0.181 km^2 in 2015 and at 0.975±0.068 km^2 in 2023, a loss of ~14% in eight years. In 2015/2016, two isolated perennial snowfields/stagnant ice regions were mapped at 0.027±0.008 km^2 and 0.119±0.036 km^2. In 2023, the former was gone while the latter lacked any snow cover and was only debris-covered stagnant ice.

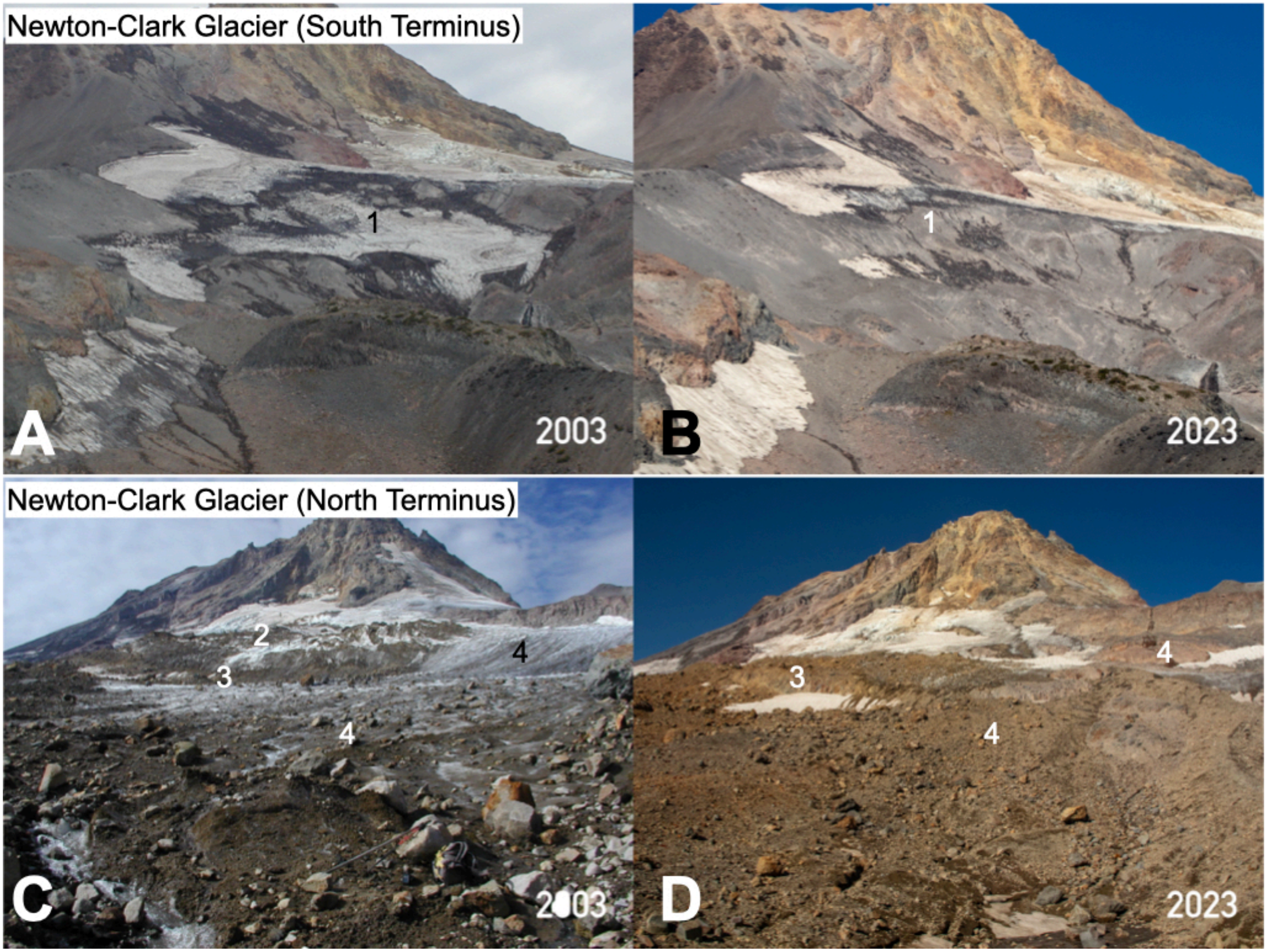

Figure S5: Southern terminus of Newton-Clark Glacier in the Clark drainage (shot location 45.34747º, -121.66964º) in 2003 (A) and 2023 (B). Northern terminus of Newton-Clark Glacier in the Newton drainage (shot location 45.37176º, -121.67088º) in 2003 (C) and 2023 (D). 1. Change in ice extent in the last 20 years where actively flowing ice in 2003 (A) had only stagnant remnants of ice in 2023 (B). 2. Recent landslide in 2003. 3. Retreat of the ice margin (C) where the terminus is located at point 3 in 2023 (D). 4. Indications of significant ice thinning and retreat in the last 20 years.

Eliot Glacier (Fig. S6) faces northeast and flows in a glacial trough that is reinforced by an extensive moraine that dates to about 1740 (Lawrence, 1948). The accumulation area is on a 12-13 ka dacite surface that shades the zone for much of the day. The terminus is heavily debris-covered due to rock fall and eolian and englacial debris (Lundstrom et al., 1993; Lillquist and Walker, 2006; Jackson and Fountain, 2007). The actively flowing glacier ice under debris was found down to ~2050 m asl with stagnant-debris-covered ice found down to ~1900 m asl in 2003. By 2023, the active-glacier margin had risen ~70 m to ~2120 m asl. In 2003, significant large crevasses and seracs flowed over rock promontories and cliffs (Fig. S6A) that were exposed in 2023 (Fig. S6B). The terminus had thinned significantly in those 20 years. Eliot's area of actively flowing ice was mapped at 1.086±0.174 km^2 in 2016 and at 0.912±0.064 km^2 in 2023, a loss of ~16% seven years. In 2016, Fountain et al.

(2023) mapped the former terminus as a region of buried stagnant ice separate from Eliot Glacier with an area of ~0.451 km^2. In 2023, this buried ice remained yet was almost completely disconnected from Eliot Glacier.

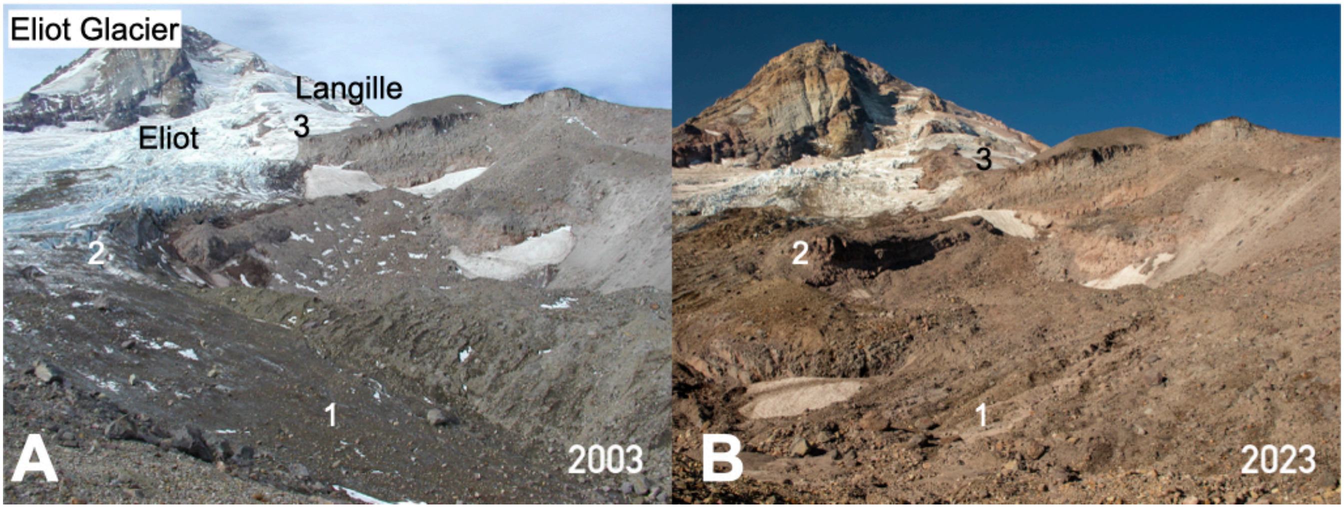

Figure S6: Eliot Glacier (shot location 45.38891°, -121.66957°) terminus in 2003 (A) and 2023 (B). 1. Significant retreat of the glacier terminus exposing bare ground. 2. Ice-margin retreat in the last 20 years that exposed bedrock promontories. 3. Note retreat of Langille Glacier over the last 20 years.

Langille Glacier (Fig. S6, S7A, B) faces north-northeast, lies between Eliot and Coe glaciers, and has a steep accumulation area before flowing over a broad slope. By 2003, the lower portions of the glacier had separated from the accumulation area and broken into four separate ice masses. Two of them still had crevasses, terminating at ~2070 m asl and ~1960 m asl. By 2023, almost all of the ice in these four ice bodies had melted away. The remaining small patches of stagnant ice were largely debris-covered. In 2015, Fountain et al. (2023) noted these stagnant ice portions as perennial snowfields (0.015±0.004 km^2, 0.011±0.003 km^2, 0.011±0.003 km^2, and 0.046±0.014 km^2), a classification that is mostly no longer applicable as barely any snow remained on these areas in 2023. Fountain et al. (2023) placed Langille's active area at 0.233±0.037 km^2. By 2023, the active-glacier area was 0.138±0.010 km^2, a loss of ~41% in eight years.

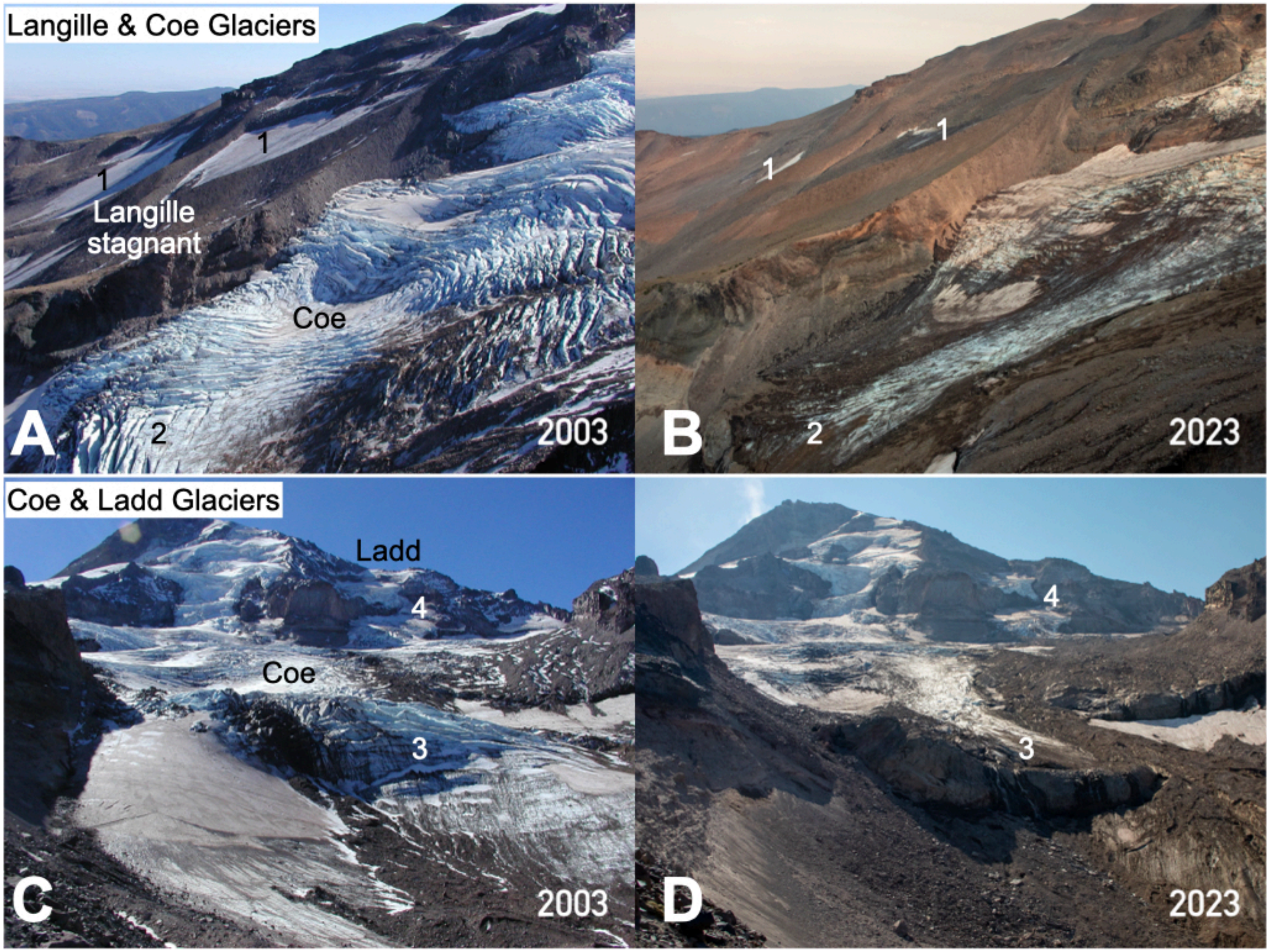

Figure S7: Langille and Coe Glaciers (shot location 45.39459º, -121.69982º) in 2003 (A) and 2023 (B). Coe Glacier (shot location 45.39701º, -121.69092º) in 2003 (C) and 2023 (D). 1. Disappearance of remnant ice of Langille Glacier. 2. Loss of an ice fall on Coe Glacier due to terminus retreat to just below the 2 in B. 3. Same loss of ice fall for Coe Glacier with its terminus now at the 3 in D. 4. Separation of Ladd Glacier from its uppermost accumulation zone that is also seen in Fig. S8.

Coe Glacier (Fig. S7) faces due north and flows in a glacier trough that is partly composed of its moraines. While Coe's terminus is fully covered in debris, this cover was less than on Eliot's terminus in 2003-2020/2021/2023. In 2003, Coe's lowest ice fall was still active with ice flowing down to ~1920 m asl. Its debris-covered-stagnant ice extended to ~1780 m asl. By 2023, the ice fall had disappeared, exposing the cliff, and the terminus had risen ~170 m to an elevation of ~2090 m asl. All the ice below this cliff was now stagnant and debris covered. While crevassing remains significant in 2023, it had reduced since 2003, with smaller and fewer crevasses. Ice thinning had also exposed larger rock cliffs. The glacier's active-ice area was mapped at 0.779±0.125 km^2 in 2016 and at 0.696±0.049 km^2 in 2023, an ~11% loss in seven years. In 2016, Fountain et al. (2023) mapped the stagnant ice that used to be part of Coe in 2003 as a separate ice body with an area of ~0.267 km^2. By 2023, this stagnant ice body had almost completely detached from the actively flowing glacier.

Ladd Glacier (Fig. S8) has a north-northwest aspect. Ladd flows in another glacial trough parallel to Coe until making a bend westward at an andesite spur that erupted ~50 ka. Thus, Ladd's lower reaches do not have the shading from solar radiation afforded Eliot and Coe by the summit of Mt. Hood. Below the spur, Ladd is buttressed to the north by a prehistoric moraine but spreads broadly to the south. In 2003, the active glacier terminus had high amounts of debris cover with three sub-lobes spread out to elevations of ~2120 m asl (north), ~2110 m asl (south), and ~2100 m asl (central), with the central lobe having seracs. In the last 20 years, Ladd's terminus rose ~230 m to a single lobe at ~2330 m asl above a previous icefall. More notably, the glacier had disconnected from its uppermost accumulation area due to ice thinning over another ice fall. Ladd's active-ice area was mapped at 0.347±0.055 km^2 in 2015, and at 0.235±0.016 km^2 in 2023, a loss of ~32% in just eight years. Fountain et al. (2023) mapped another four snow/ice bodies that had separated from Ladd: two that were in the process of stagnating and were stagnant as of 2023 (0.034±0.001 km^2 and 0.051±0.002 km^2) and another two perennial snowfields/stagnant ice bodies (0.017±0.005 km^2 and 0.025±0.007 km^2). In 2023, these were all stagnant ice bodies covered by debris, lacking snow cover.

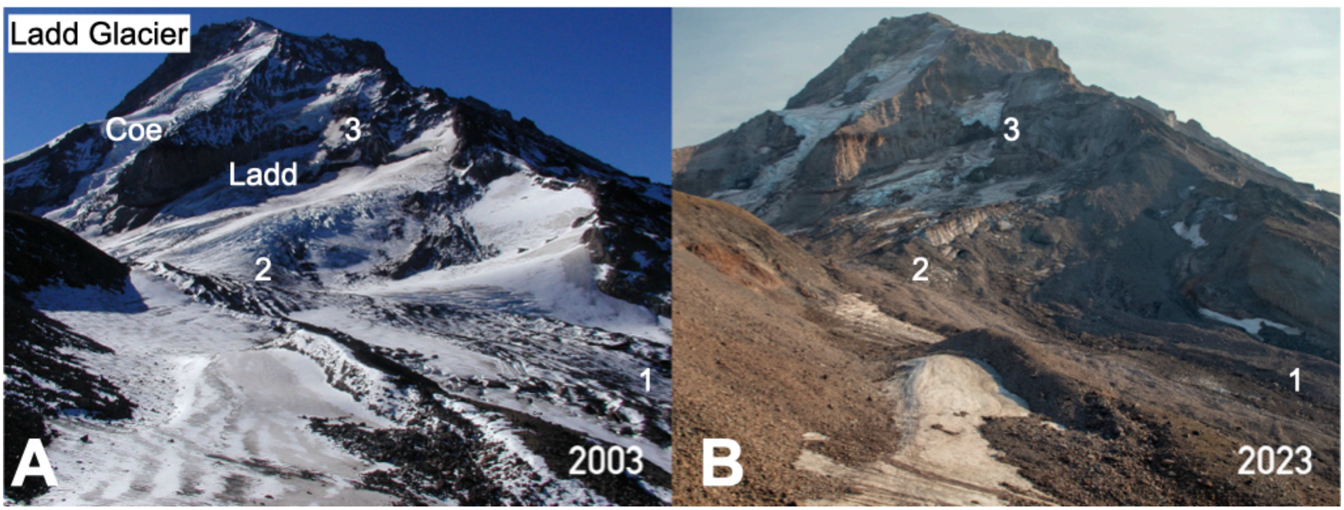

Figure S8: Ladd Glacier (shot location 45.39718º, -121.70424º) in 2003 (A) and 2023 (B). 1. Retreat of the ice margin where active ice in 2003 was detached stagnant ice in 2023. 2. Ice fall that is now the current terminus of Ladd. 3. Separation of Ladd from its uppermost accumulation area.

Glisan Glacier (Fig. S9) had a northwest aspect. By 2003, the glacier had broken up into four ice masses, only two of which had crevasses: one terminating at ~2040 m asl and the other at ~1930 m asl (Fig. S9A). Both of these ice masses had previously formed distinct lateral and terminal moraines from which they were retreating in 2003. In 2023, the remnant with the higher terminus was nearly gone while the other with the lower terminus had a stagnant-ice area of 0.009±0.0006 km^2. The actively flowing terminus thus rose in elevation by at least 220 m in the last 20 years (i.e., from its 2003 elevation to the top of the 2023 stagnant ice mass). One of the 2003 stagnant ice masses was completely gone while the other remained (Fig. S9D). For 2015, Fountain et al. (2023) documented the glacial remnant against the bedrock ridge as still active with an area of 0.041±0.006 km^2 and classified the other 2003 remnant as a perennial snowfield (0.042±0.013 km^2). Both these classifications were out-ofdate as of 2023 and Glisan Glacier no longer existed as a flowing glacier.

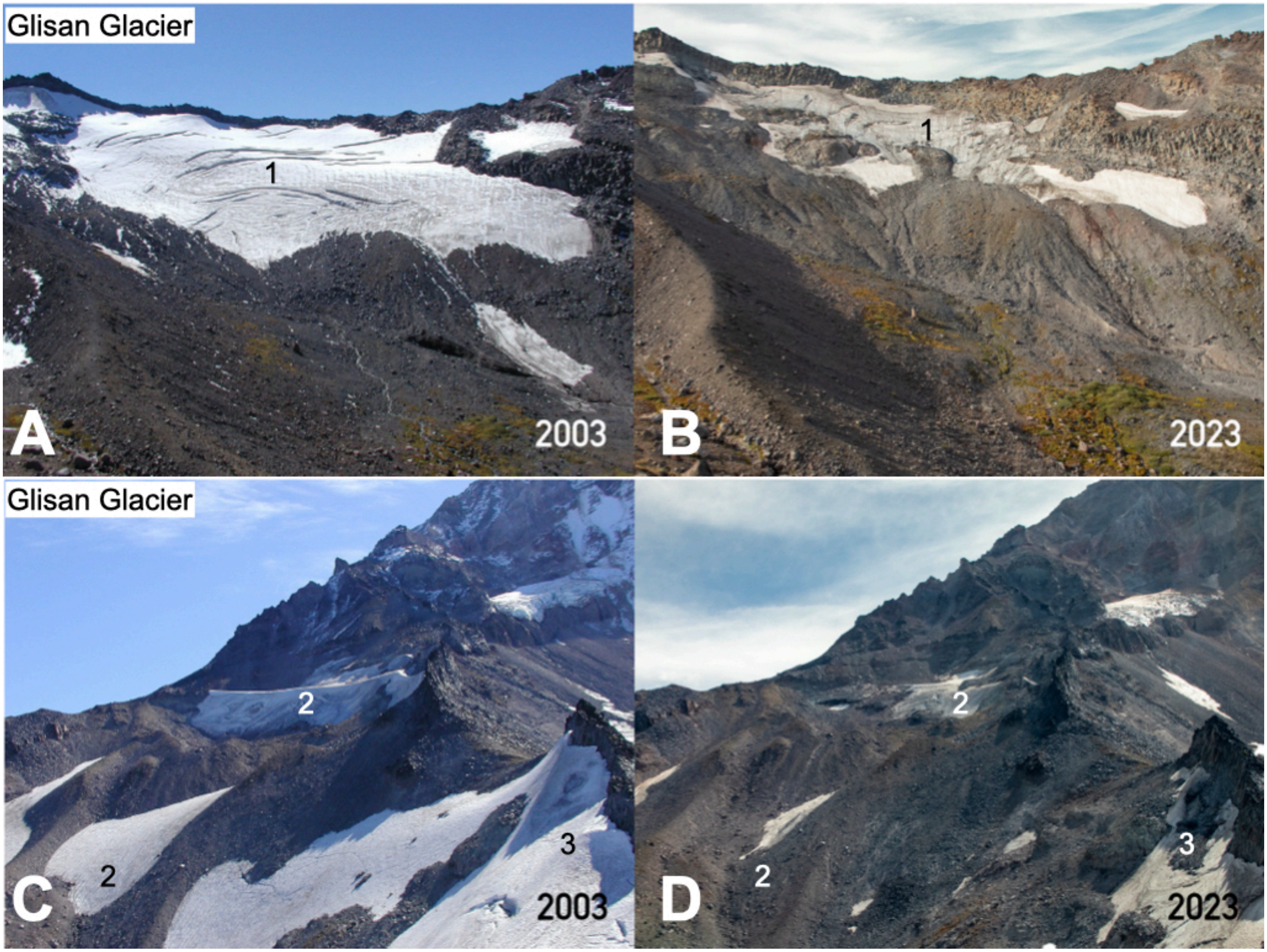

Figure S9: Glisan Glacier remnant looking south (shot location 45.39531º, -121.71777º) in 2003 (A) and 2023 (B). Glisan Glacier remnants looking east (shot location 45.39093º, -121.72249º) in 2003 (C) and 2023 (D). 1. Transition of last actively flowing part of Glisan in 2003 (A) to stagnant ice by 2023 (B). 2. Loss of stagnant ice with the upper ice mass still remaining in 2023 (D). 3. Transition of last actively flowing part of Glisan in 2003 (C) to stagnant ice by 2023 (D).

Sandy Glacier (Fig. S10) faces west-northwest in a broad valley between two andesitic ridges (erupted 50-100 ka). This glacier is the only one on Mt. Hood with an ice cave system at present. In 2003, the glacier had three terminal lobes, the lowest of which reached ~1890 m asl and had two ice caves. One of the caves opened higher up on the glacier and may have connected with an ice cave system discovered in the accumulation area after our observation. The main and lowest terminus in 2003 was covered by what appeared to be a rock avalanche but the rest of the glacier was largely free of debris. In 2023, Sandy's main terminus had retreated to ~2130 m asl, rising ~240 m in elevation. Two ice caves still existed. Debris cover had greatly increased on the glacier, covering even large parts of its accumulation area. The glacier's area was mapped at 0.751±0.120

km^2 in 2016, and at 0.631±0.044 km^2 in 2023, a loss of ~16% in seven years. Three other separate perennial snowfields were mapped in 2015 (areas of 0.024±0.007 km^2, 0.011±0.003 km^2, 0.012±0.004 km^2) that in 2023 lacked snow.

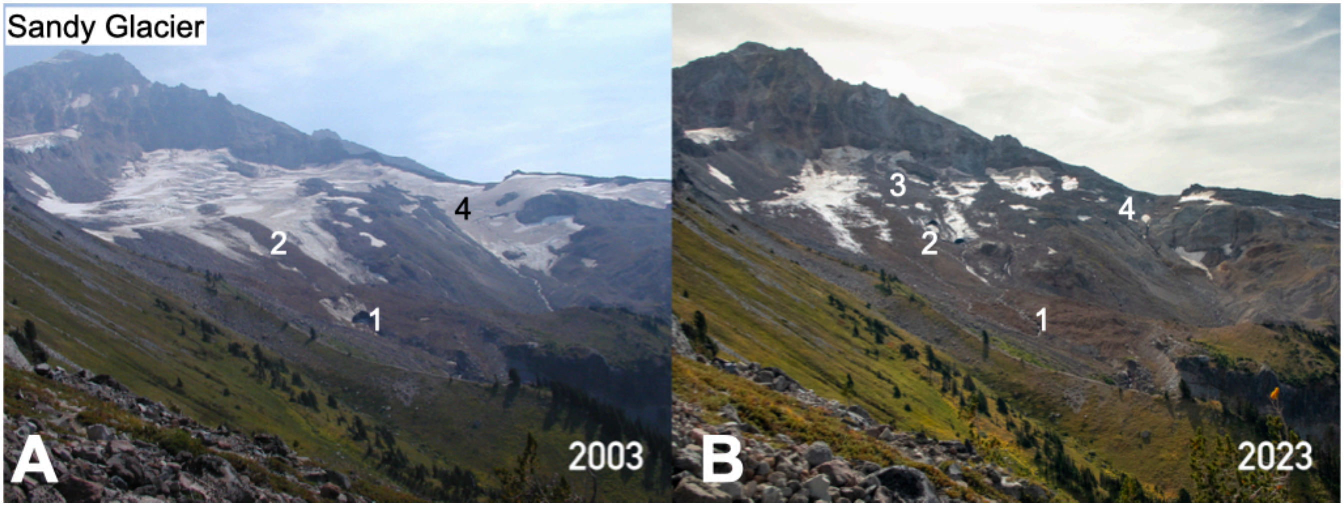

Figure S10: Sandy Glacier (shot location 45.39477º, -121.73124º) in 2003 (A) and 2023 (B). 1. 2003 terminus with ice cave (A) that is now stagnant ice (B). 2. 2023 terminus location and ice caves (B) that were in the centre of the glacier in 2003 (A). 3. Accumulation of rock fall on the glacier in the last 20 years. 4. Retreat of glacier ice that is now exposed bedrock.

Reid Glacier (Fig. S11) faces west in another broad valley between two bedrock ridges that erupted >100 ka, with the southern ridge providing shade to the glacier's terminus from direct solar radiation for much of the day. Its terminus has in the past flowed over a large cliff that could limit further downslope expansion of the glacier. In 2003, most of the terminus resided above the cliff while three areas of the terminus spilled over the cliff at ~2240 m asl. The central portion of the glacier still connected to recently stagnated (as evidenced by down-wasting crevasses) debris-covered ice below the cliff reaching to ~1920 m asl. In 2023, the glacier terminus resided entirely above the cliff, and the section of the terminus to the north that spilled over the cliff as an icefall in 2003 was stagnant. Some heavily debris-covered stagnant ice resided below the cliff band. Reid had experienced significant thinning from 2003 to 2023, with more debris cover from rockfall and landslides, including parts of its accumulation area. The terminus had risen ~110 m since 2003 to ~2350 m asl. In 2015, Reid's area was mapped at 0.469±0.005 km^2, and at 0.417±0.029 km^2 in 2023, a loss of ~11% in eight years.

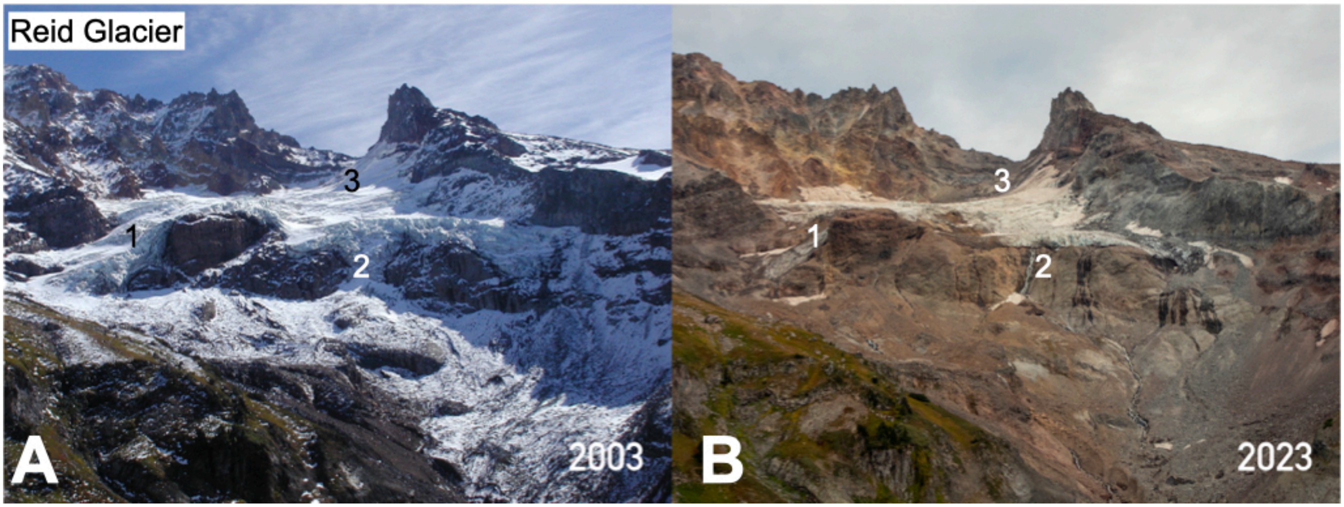

Figure S11: Reid Glacier (shot location 45.37559º, -121.74100º) in 2003 (A) and 2023 (B). 1. Loss of ice fall over ridge in last 20 years. 2. Loss of ice fall over ridge in last 20 years. 3. Thinning and debris accrual in the upper accumulation zone.

In addition to the above dimensions of named glaciers on Mt. Hood, Fountain et al. (2023) noted in 2015/2016 another two small unnamed glaciers (0.060±0.0006 km^2 and 0.033±0.0003 km^2) and three other perennial snowfields/stagnant ice regions (0.033±0.010 km2, 0.012±0.004 km^2, and 0.011±0.003 km^2). By 2023, the two unnamed glaciers had stagnated with concave termini and lacked snow cover; the three perennial snowfields still had some snow cover.

Sentinel-2 Satellite Image Inventory

The following image dates for Sentinel-2 imagery were used in the iterative mapping process as provided by CalTopo.com.

08-30-2020
09-09-2020
09-29-2020
10-09-2020
10-08-2021
30-08-2021
10-08-2022
20-08-2022
30-08-2022
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19-09-2022
04-10-2022
19-10-2022

10-08-2023

15-08-2023

09-09-2023

19-09-2023

Table S1. Glacier length records from Lillquiest and Walker (2006) with additional change up 2023.

Year	White River (m)	Newton-Clark (m)	Eliot (m)	Coe (m)	Ladd (m)
1901	2690	1312	4359	3734	2902
1928			4271	3652	2830
1938	2129	1162	4229	3615	2827
1946	2156	1051	4178	3557	2787
1959	2428	1231	4076	3262	
1967	2170	1268	4096	3366	2676
1972	2192	1141	4175	3420	2692
1979	2333	1295	4095	3400	2653
1984	2192	1364	4047	3404	2622
1989	2214	1346	3984	3376	1700
1995	2114	1093	3944	3361	1784
2000	2073	1250	3566	3322	1800
2023	1743	810	2546	2272	1030

Table S2. Sensitivity test for glacier change from 2000 to 2023 by including additional stagnant ice/perennial snowfield area from 2015/2016 of Fountain et al. (2023) with the 2023 areas of the seven glaciers that have 20th century area records (Jackson and Fountain, 2007). The third column is the stagnant ice/perennial snowfield area in 2015/2016 that was added to the 2023 area (second column) to make a new 2023 area (fourth column). This new area was then used to determine a minimum change in area since 2000 (fifth column), with the rate (last column) compared against 20th century rates (sixth and seventh columns). Note that these 20th century rates do not include any stagnant ice in their areas and thus this is only a sensitivity test as different definitions of what constitutes a glacier were used.

Glacier	2023 Area km^2 (uncert)	2015/16 + Area km^2 (uncert)	2023 +Area km^2 (uncert)	2000-2023 % Δ Area (uncert)	1907-2000 % yr^{-1} (uncert)	Max 20th C. % yr^{-1} (uncert)	2000-2023 % yr^{-1} (uncert)
White River	0.271 (0.019)	0.048 (0.014)	0.319 (0.024)	27.5 (2.8)	0.62 (0.08)	1.41 (0.19)	1.20 (0.03)
Newton-Clark	0.975 (0.068)	0.146 (0.037)	1.121 (0.077)	27.2 (2.7)	0.27 (0.03)	0.47 (0.04)	1.18 (0.03)
Eliot	0.912 (0.064)	0.451 (-)	1.363 (0.064)	17.9 (1.5)	0.18 (0.02)	0.44 (0.03)	0.78 (0.01)
Coe	0.696 (0.049)	0.267 (-)	0.963 (0.049)	20.4 (1.7)	0.15 (0.02)	0.29 (0.03)	0.89 (0.02)
Ladd	0.235 (0.016)	0.127 (0.009)	0.362 (0.019)	49.0 (4.3)	0.36 (0.04)	0.63 (0.05)	2.13 (0.09)
Sandy	0.631 (0.044)	0.046 (0.009)	0.677 (0.045)	33.7 (3.2)	0.39 (0.05)	0.99 (0.13)	1.46 (0.05)
Reid	0.417 (0.029)	0.000 (0.000)	0.417 (0.029)	21.3 (2.2)	0.35 (0.06)	0.84 (0.14)	0.90 (0.09)
Seven combined	4.282 (0.127)	1.085 (0.041)	5.367 (0.134)	24.5 (0.9)	0.31 (0.02)	0.56 (0.02)	1.07 (0.01)

References

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