

# Application of Aerial InSAR to Measure Glacier Elevations

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## Key Points:

- Aerial InSAR can rapidly map the topography of alpine glaciers over a broad region.
- Elevations compare favorably to lidar,  $+0.17 \pm 1.78$  m at spatial scale of 3 m.
- The mean rate of glacier elevation change (specific volume) is  $-0.3 \pm 0.2$  m yr<sup>-1</sup> for the past 56 years with rates increasing since 1980.

## 21 **Abstract**

22  
23 Glaciers and perennial snowfields are important to alpine ecosystems and regional  
24 hydrology. Quantifying volume change of a population of glaciers widely distributed  
25 over a region is difficult and expensive. We employed NASA's novel Airborne Glacier  
26 and Ice Surface Topography Interferometer (GLISTIN) to rapidly map surface  
27 topography of alpine glaciers across the western USA. In five flight days 3289 glaciers  
28 and perennial snowfields were surveyed. Comparison with lidar over control sites showed  
29 a mean difference of  $+0.17 \pm 1.78$  m at a spatial scale of 3 m. Data coverage increased  
30 and elevation uncertainty decreased with the mosaicking of multiple passes due to the  
31 complex terrain. Elevation change since the National Elevation Dataset shows a thinning  
32 (and volume loss) over the last ~56 years, averaging  $-0.3 \pm 0.2$  m and accelerating since  
33 1980. GLISTIN can be a valuable tool for rapidly mapping ice surfaces in the alpine  
34 environment.

## 35 **Plain Language Summary**

36  
37  
38 Glaciers and perennial snowfields are important water sources to alpine ecosystems and  
39 regional hydrology. To quantify their contribution their volume change is measured by  
40 mapping elevation changes of the ice surface. However, quantifying volume change for a  
41 population of glaciers widely distributed over a region is difficult and expensive. We  
42 employed NASA's airborne radar (GLISTIN) to rapidly map surface topography of  
43 alpine glaciers across the western USA. In only five flight days 3289 glaciers and  
44 perennial snowfields were surveyed. GLISTIN data over control-regions were compared  
45 to lidar, an independent elevation measure using lasers, and showed small differences  
46 indicating this method can be a valuable and cost-effective tool to track glacier change in  
47 the future. Comparing the new elevations against historic elevations from USGS maps a  
48 dramatic thinning (and volume loss) over the last ~60 years.

## 49 **1. Introduction**

50  
51  
52 Glacier melt is important to runoff in high alpine landscapes. At a local scale, melting  
53 glaciers maintain streamflow during the dry, late summer months after the seasonal snow

54 has melted (Fountain & Tangborn, 1985; Moore et al., 2009). Shrinking glaciers lose ice  
55 volume and supply more water to streams and rivers than anticipated from precipitation.  
56 Although this may be a temporary benefit, particularly in dry regions, their ability to  
57 buffer seasonal runoff in future is reduced, making watersheds more vulnerable to  
58 drought (Hall & Fagre, 2003; Moore et al., 2009). At a global scale, mass transfer of  
59 water from storage as ice to water runoff increases global sea-levels (Meier, 1984; Pfeffer  
60 et al., 2014; Zemp et al., 2019).

61  
62 Traditionally, tracking glacier mass change was a field effort based on measuring the gain  
63 and loss of snow and ice at points on the glacier (Kaser et al., 2003; Ostrem & Brugman,  
64 1991). Although these efforts produce high-quality results showing spatial variations in  
65 mass change across a glacier only a few glaciers can be so monitored by any agency  
66 (Andreassen et al., 2005; O’Neel et al., 2019). Remote-sensing methods can be used to  
67 cover broad regions using an alternative approach that estimates mass change from  
68 volume change. Differential interferometric synthetic aperture radar (InSAR) can map  
69 surface elevation changes and offers the advantage of an all-weather, day/night  
70 capability, a particularly valuable tool in often cloudy alpine environments (Rosen et al.,  
71 2000). Satellite-borne applications have revolutionized our understanding of Antarctica  
72 and Greenland (Mouginot et al., 2019; Shepherd et al., 2018), and more recently, the  
73 larger alpine glaciers (Millan et al., 2022). Challenges using InSAR include shadowing,  
74 decorrelation due to layover, phase unwrapping, and temporal landscape changes  
75 (Eineder & Holzner, 2000; Rees, 2000).

76  
77 Here, we test a novel approach for determining surface elevations on alpine glaciers using  
78 an airborne single-pass InSAR, NASA’s Glacier, and Ice Surface Topography  
79 Interferometer (GLISTIN; Moller et al., 2017). Unlike differential/repeat-pass InSAR,  
80 GLISTIN collects two radar images simultaneously, allowing elevations to be derived  
81 from a single flight pass and are thus not sensitive to temporal decorrelation between  
82 observations. Mounted on a jet aircraft, GLISTIN can image large areas in a short time  
83 and has been used to map the relatively gentle topography of large glaciers and ice sheets

84 (Hensley et al., 2016; Moller et al., 2019). We evaluate its performance to map small  
85 alpine glaciers in complex terrain across a broad region. In addition, the updated glacier  
86 elevations are differenced from the National Elevation Data (Gesch, 2002) to calculate  
87 glacier elevation change across the western US.

88

## 89 **2. Data and Methods**

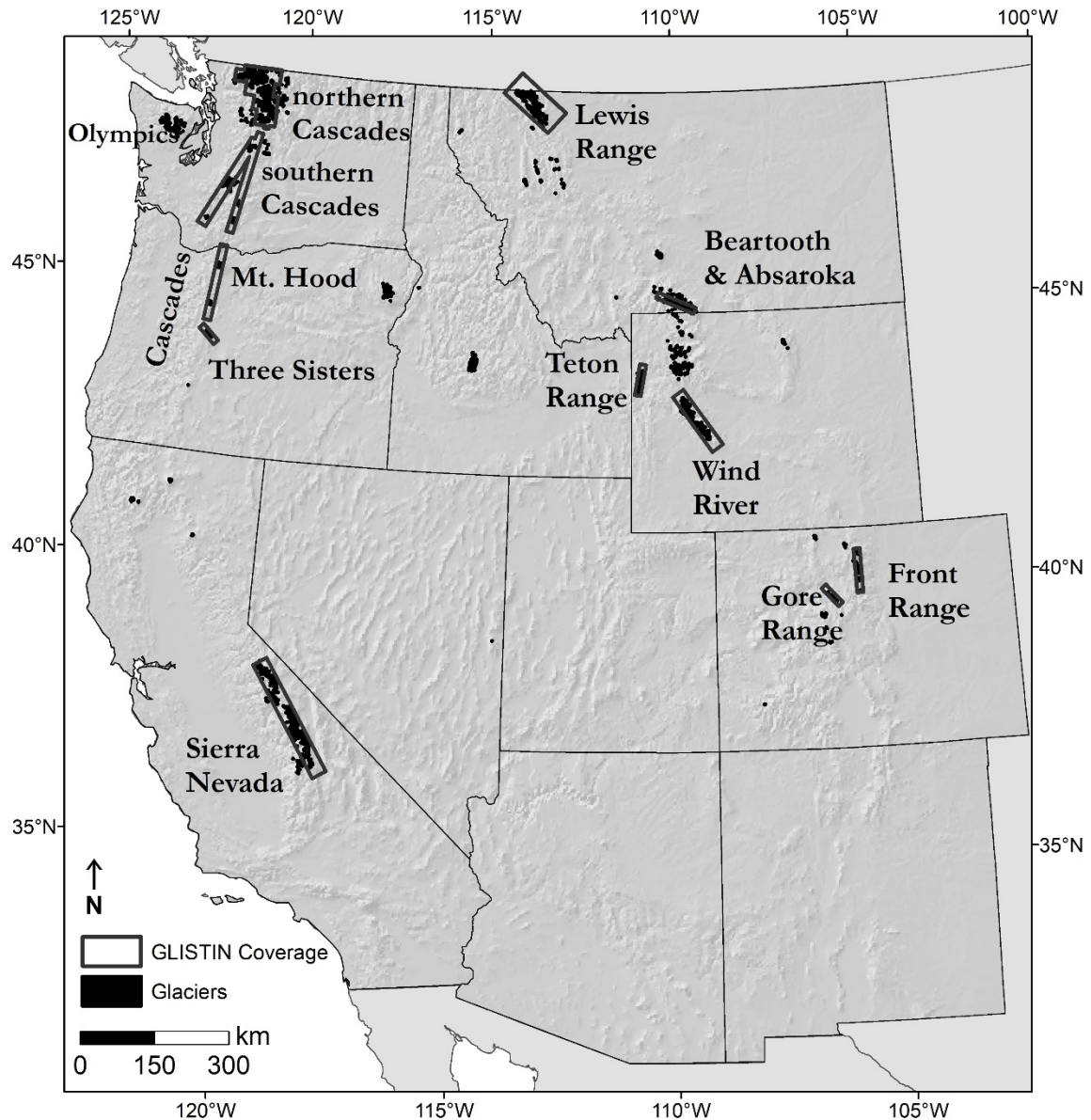
90

### 91 **2.1 Study Area**

92

93 The study region is the American West, defined as the continental United States west of  
94 the 100th meridian enclosing about  $2 \times 10^6$  km<sup>2</sup> and home to about 5036 glaciers and  
95 perennial snowfields ( $\geq 0.01$  km<sup>2</sup>) as of the late 20<sup>th</sup> century (Figure 1; Fountain et al.,  
96 2017). The region is made up of three large mountain ranges, the Rocky Mountains, the  
97 Cascade Range, and the Sierra Nevada. Many peaks exceed 4000 m in. The largest  
98 concentration of glaciers, and lowest elevation (2000 m - 3000 m asl) is in the maritime  
99 climate of the Pacific Northwest (Oregon, Washington, north-west Montana,). The  
100 remaining glaciers are in continental climates elsewhere at high elevations, > 3000m.

101



**Figure 1.** Map of glaciers and perennial snowfields (black dots) in the Western U.S. The boxes show regions surveyed by GLISTIN.

Regional studies have shown drastic decreases in glacier area exceeding 50% over the last century (DeVisser & Fountain, 2015; Fagre et al., 2017; O’Neal et al., 2019). The rate of change has not been constant or spatially uniform (Basagic & Fountain, 2011; Hoffman et al., 2007; O’Neal et al., 2015). Glacier volume changes, estimated by differencing topography over time, show a loss on Mount Rainier, WA, of  $-0.65 \text{ km}^3$ ,

111 average specific mass loss rate of  $-0.16 \text{ m w.e yr}^{-1}$  (1970 - 2007/2008; Sisson et al.,  
112 2011). Menounos et al. (2018) estimated a volume loss of  $-127.65 \pm 45.17 \text{ km}^3$ ,  $-0.42 \pm$   
113  $0.15 \text{ m w.e.}$  between 2000 and 2018 for most of the glaciated terrain in Western North  
114 America.

## 115 116 2.2 GLISTIN

117  
118 GLISTIN is a Ka-band radar (8.4 mm, 35.66 GHz) system that utilizes two horizontally  
119 polarized antennas, 0.25 m apart in elevation, both of which are capable of transmitting  
120 and receiving (Moller et al., 2019). Unlike repeat-pass InSAR, GLISTIN's dual antennas,  
121 collect data simultaneously. The Ka-band center frequency enables high accuracy with a  
122 compact architecture and reduces snow penetration compared to lower frequencies. This  
123 cross-track InSAR system is capable of providing not only the position of each image  
124 point in along-track and slant range as with traditional SAR but also the height of that  
125 point via the interferometric phase. Because the phase repeats after  $2\pi$ , it must be  
126 "unwrapped" to determine its unique location and height relative to a reference surface  
127 (Moller et al., 2011; Rosen et al., 2000). The system is contained in an external pod  
128 beneath NASA's Gulfstream-III aircraft with left looking view angles of  $15\text{-}50^\circ$  from  
129 nadir. The system is coupled to inertial navigation and global position that provide pitch  
130 and roll of the aircraft as well as its precise position in space. Nominal flight altitudes are  
131 about 12,500 m above sea-level with a ground swath width of about 12 km and its typical  
132 air speed is  $720 \text{ km hr}^{-1}$ .

133  
134 To guide the aerial survey, the locations of the glaciers were retrieved from Fountain et  
135 al. (2017). Flight passes were typically flown in pairs, each in an opposite direction, to  
136 reduce gaps in backscatter from radar shadow or layover in the mountainous terrain. In a  
137 few regions additional perpendicular flight passes were also flown. The georectified  
138 height-maps from each pass were mosaicked into a 3-meter pixel-size digital elevation  
139 model (DEM; Hensley et al., 2016) and projected into the Universal Transverse Mercator  
140 (UTM) coordinate system. Self-reported elevation accuracy is 'height-precision', a  
141 statistical estimate based on the interferometric correlation of each individual radar pixel

142 making up the 3 m mosaicked pixel (Moller et al., 2011). In the final mosaicked DEM,  
143 the elevation of each pixel is the weighted sum of elevations from individual passes and  
144 the weights are inversely proportional to the height-precision (Hensley et al., 2016). The  
145 vertical absolute uncertainty of GLISTIN-derived topography was found to be about  $\pm$   
146 0.30 m over bare non-snow-covered terrain (Schumann et al., 2016). Data collection and  
147 processing were provided by the Jet Propulsion Laboratory at California Institute of  
148 Technology, Pasadena, CA.

## 149 150 2.3 Accuracy

151  
152 The accuracy of GLISTIN elevations was ground-truthed by differencing lidar DEMs  
153 from GLISTIN DEMs (Table SOM2). All lidar data were converted from its native  
154 coordinate system to WGS84 to UTM using Vdatum (Version 3.8, 2017, National  
155 Oceanic and Atmospheric Administration, Washington, DC), inducing an error of about  
156 0.076 m (self-reported by Vdatum during conversion) and resampled to 3 m to match the  
157 GLISTIN DEMs spatial posting, using bilinear interpolation. To calculate elevation  
158 change the  $\frac{1}{3}$  arc-second NED was converted to UTM (WGS84) using Vdatum and  
159 resampled to 10 m using bilinear interpolation. GLISTIN and lidar elevations were also  
160 resampled to 10 m using bilinear interpolation to match the NED. The relative accuracy  
161 of GLISTIN, lidar, and the NED were inter-compared at four barren earth snow-free  
162 control zones in the Cascade Range of Oregon and Washington where all three estimates  
163 of elevation were available. Each control zone is a patchwork of co-located but isolated  
164 terrains. Barren earth terrains were derived from the 'barren' class of the 2016 National  
165 Land Cover Database (<https://www.mrlc.gov/data/nlcd-2016-land-cover-conus>).  
166 GLISTIN's performance imaging ice/snow surfaces was examined by comparing  
167 elevations to lidar data acquired on Mount Adams, Washington, which was flown 28  
168 days prior to the GLISTIN flights. We expect GLISTIN to yield somewhat lower  
169 elevations due to melting of the snow and ice.

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## 173 2.4 Area and Volume Change

174  
175 The reference area and elevation of the glaciers and perennial snowfields are derived  
176 from (Fountain et al., 2017) and a ‘historic’ version of the NED (Gesch et al., 2002),  
177 respectively. Both are based on the original U.S. Geological Survey 1:24000 topographic  
178 maps from which the glacier outlines and elevations were derived. The maps in the  
179 western US were drawn over a period of years (1940s-1980s. Resolution of the NED is  $\frac{1}{3}$   
180 arc-second ( $\sim 10$  m), and the horizontal and vertical coordinate systems are North  
181 American Datum of 1983, North American Vertical Datum of 1988, respectively. The  
182 NED is continually being updated and it was necessary to retrieve the original ‘historic’  
183 version from multiple sources (Table SOM1).

184  
185 Volume change was estimated by differencing the GLISTIN elevations from the NED  
186 elevations within the original perimeter and for only those glaciers with  $\geq 80\%$  GLISTIN  
187 coverage. Le Bris and Paul (2015) showed that good estimates of volume change can be  
188 achieved with the elevation postings cover at least 80% of the glacier area. Reasonable  
189 estimates of volume change can be obtained for coverages as low as 40%, however  
190 results depend on interpolation method (McNabb et al., 2019), so we adopted the more  
191 conservative threshold of 80% used by Le Bris and Paul (2015). In order to compare  
192 volume loss between large and small glaciers and because the historic mapping occurred  
193 over a time-span of decades across the western US, results are expressed as the rate of  
194 specific volume (volume/area) change ( $\text{m}^{-3} \text{m}^{-2} \text{yr}^{-1}$  or  $\text{m} \text{yr}^{-1}$ ).

195  
196 Uncertainty of volume change,  $\sigma_{\Delta V}$ , is calculated for each individual glacier or perennial  
197 snowfield, using the vertical and area uncertainties (Menounos et al., 2018),

$$198 \quad \sigma_{\Delta V} = \sqrt{(\sigma_{\Delta z} A_g)^2 + (\sigma_A \Delta z)^2}, \quad (1)$$

199  
200 where  $\sigma_{\Delta z}$  is the RMSE of elevation differences between GLISTIN and the NED for all  
201 barren earth control zones, for the region in which the glacier or perennial snowfield is  
202 located,  $A_g$  is the original (historic) area of the glacier or perennial snowfield,  $\Delta z$  is the

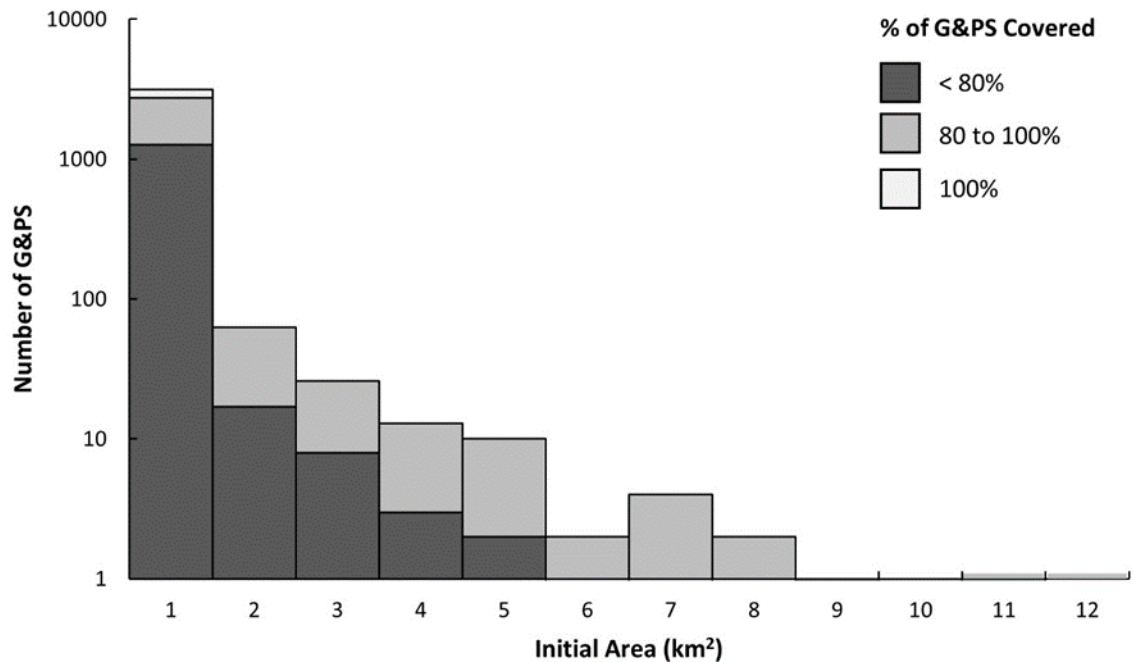


203 average elevation change of the glacier or perennial snowfield, and  $\sigma_A$  is area uncertainty.  
 204 Uncertainty of the original areas is considered 9% (Fountain et al., 2017).

### 205 206 **3. Results and Analysis**

#### 207 208 **3.1 Data collection**

209  
 210 The GLISTIN flights imaged the glacier-populated mountains of the American West for  
 211 5 flight days, between September 12 to 28, 2016, covering about 41,000 km<sup>2</sup> (Figure 1).  
 212 Due to an unexpected reassignment of the aircraft, several mountain ranges were not  
 213 included, most notably the Olympic Mountains, WA, and the Absaroka Range, WY.  
 214 Within the regions surveyed 3889 glaciers and perennial snowfields are present.  
 215 GLISTIN coverage of each varied from 0 to 100% with a median of 81%. The total  
 216 number of features with  $\geq 80\%$  coverage was 1770 (309 km<sup>2</sup>, 53% of the total area of  
 217 surveyed G&PS; figure 2).  
 218



219  
 220 **Figure 2.** Histogram of the initial area of glaciers and perennial snowfields and the  
 221 fraction of area mapped by GLISTIN. Initial area refers to the area from the U.S.  
 222 Geological Survey's 1:24000 map series. The x-axis value is the maximum for each bin.

223

224

225 As expected, increasing the number of flight passes over the same area increased the  
226 backscatter coverage. For one flight pass backscatter was received from 17% of the entire  
227 illuminated area, for two flights 66%, four flights, 86%, and for eight flights 94% (Table  
228 SOM3). No significant difference was observed in backscatter coverage of snow/ice  
229 surfaces compared to ice-free surfaces, and within glaciers no significant differences  
230 between snow-covered regions and ice-exposed regions. Backscatter reception was only  
231 significantly correlated with terrain slope with greater loss on steeper slopes.

232

### 233 3.2 Accuracy

234

235 The GLISTIN DEMs for three of the four barren earth control zones were compiled from  
236 multiple passes. The fourth control zone (Mount Adams, WA) was comprised of single  
237 pass data and was examined separately. For the three multi-pass barren earth control  
238 zones the GLISTIN – lidar (3 m posting) mean difference was  $+0.17 \pm 1.78$  m (Table  
239 SOM4). Comparing GLISTIN and the NED over the same regions (10 m posting), the  
240 mean difference and standard deviation was much larger,  $+1.05 \pm 6.38$  m. This is due to  
241 the much larger uncertainty in the NED elevations of 3.74 m, which is based mostly on  
242 control points located in lower elevation and less complex terrain (Gesch, 2007). The  
243 mean lidar-NED difference  $-0.89 \pm 5.83$ , supports this inference. For the control zones on  
244 Mount Adams, the mean elevations difference of single-pass GLISTIN - lidar (3 m  
245 posting) was  $-0.00 \pm 3.20$  m, whereas for the snow/ice surfaces it was  $-0.86 \pm 3.76$  m.  
246 The negative difference for the snow/ice surfaces is to be expected given the melting that  
247 occurred over the 28-day period between the initial lidar survey followed by the  
248 GLISTIN survey. Given that the snow is wet during this time of year and interferometric  
249 penetration is negligible (Hensley et al., 2016).

250 With respect to interferometric radar errors it is important to note that the height precision  
251 is dominated by the instrument random noise. This relative error is high frequency and  
252 will scale with spatial averaging of uncorrelated pixels or independent samples. The  
253 same is not true for the height accuracy or systematic (mean) offset which does not

improve with averaging as they are correlated. Therefore, if we calculate the RMSE for more coarse spatial postings this metric will reduce significantly (with the random /precision inversely proportional to the square-root of the effective number of independent looks (Hensley et. al. 2016). For this paper we analyze GLISTIN data at a spatial posting of 3m due to the small footprint of many of these glaciers. However, one can expect significantly improved height precision, and thereby RMSE for large glaciers via spatial averaging. The low mean difference (i.e. accuracy) observed for the barren areas indicates that extremely low height errors are achievable with sufficient spatial averaging to reduce the random component (Schumann et. al. 2016; Moller et.al. 2019)

Although no correlation was observed between mean elevation difference (GLISTIN - lidar) and surface slope, the standard deviation increased from about 1.7 m for slopes between 20° and 30° to 3.8 m for slopes between 50° and 60°. The RMSE (GLISTIN-NED) increased from 6.1 m for slopes 20° to 30° to 10.2 m for slopes between 50° and 60°. The rate of phase change is a function of the interferometric measurement geometry and is directly proportional to the local slope. Phase unwrapping becomes more difficult as the slope increases so an increased RMSE in extreme topography is to be expected. The orientation of single-pass GLISTIN relative to the terrain surface affects the elevation difference. The mean elevation difference (GLISTIN-lidar) was smaller for surfaces facing towards GLISTIN,  $+0.01 \pm 2.07$  m, than surfaces facing away,  $+0.07 \pm 4.03$  m.

### 3.3 Volume change

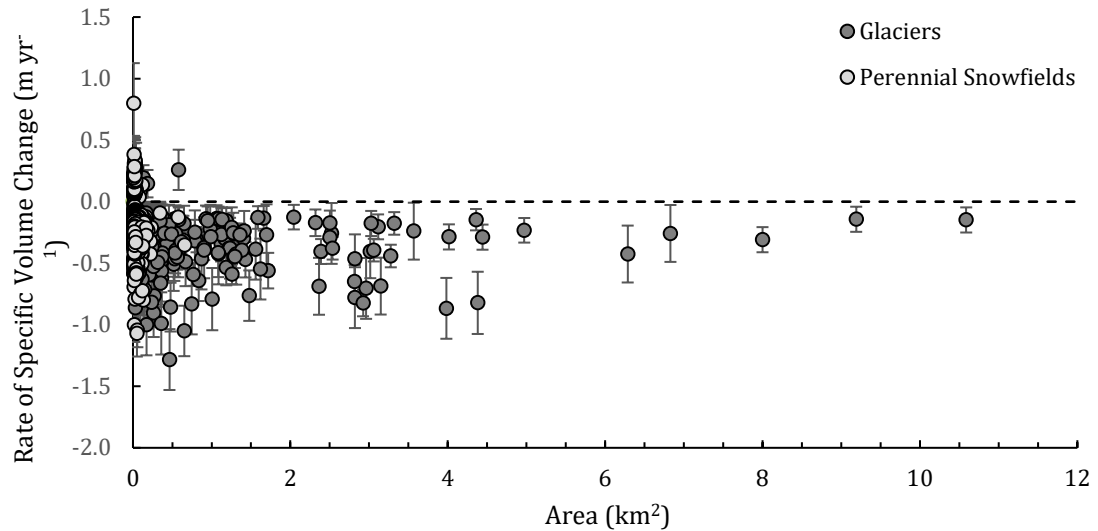
Volume change was estimated for 1770 glaciers and perennial snowfields (54% of total) consisting of 351 glaciers and 1419 snowfields. Overall mean uncertainty, based on barren earth control zones across the west (Table SOM5), was  $-0.37 \pm 7.31$  m. Rejecting those specific volume changes that were smaller than uncertainty yielded 231 glaciers totaling 198.84 km<sup>2</sup> and 551 perennial snowfields (21.31 km<sup>2</sup>). Comparing our volume change to a prior estimate for Mt. Rainier, Washington (Sisson et al., 2011), showed that the prior estimate, based on a lidar-NED difference, of -8.6 m (1970-2007) is within the

283 uncertainty of our value ,  $-9.7 \pm 4.8$  m (1970-2016). That our estimate showed a greater  
 284 mass loss is consistent with the longer time period of comparison.

285  
 286 Most glaciers and perennial snowfields lost mass (Figure 3). The median rate of change  
 287 for glaciers,  $-0.3 \pm 0.2$  m yr<sup>-1</sup>, and for snowfields,  $-0.2 \pm 0.2$  m yr<sup>-1</sup>. Four glaciers (2%)  
 288 and 56 (10%) perennial snowfields increased in volume; their locations are not region  
 289 specific. These features are characterized by small area, median 0.02 km<sup>2</sup> (all but one <  
 290 0.2 km<sup>2</sup>), steeper slopes, and higher elevations. The features that gained volume were at  
 291 significantly higher elevations and steeper slopes (median 3100 m, 28°) compared to  
 292 those that lost volume, (median 2335 m 25°;  $p < 0.05$ , Mann-Whitney U). The time series  
 293 of ice mass loss in the Cascade Range, Washington is relatively complete compared to  
 294 other regions and show increasing mass loss with time (Figure 4). The rate of change  
 295 increased significantly since 1980.

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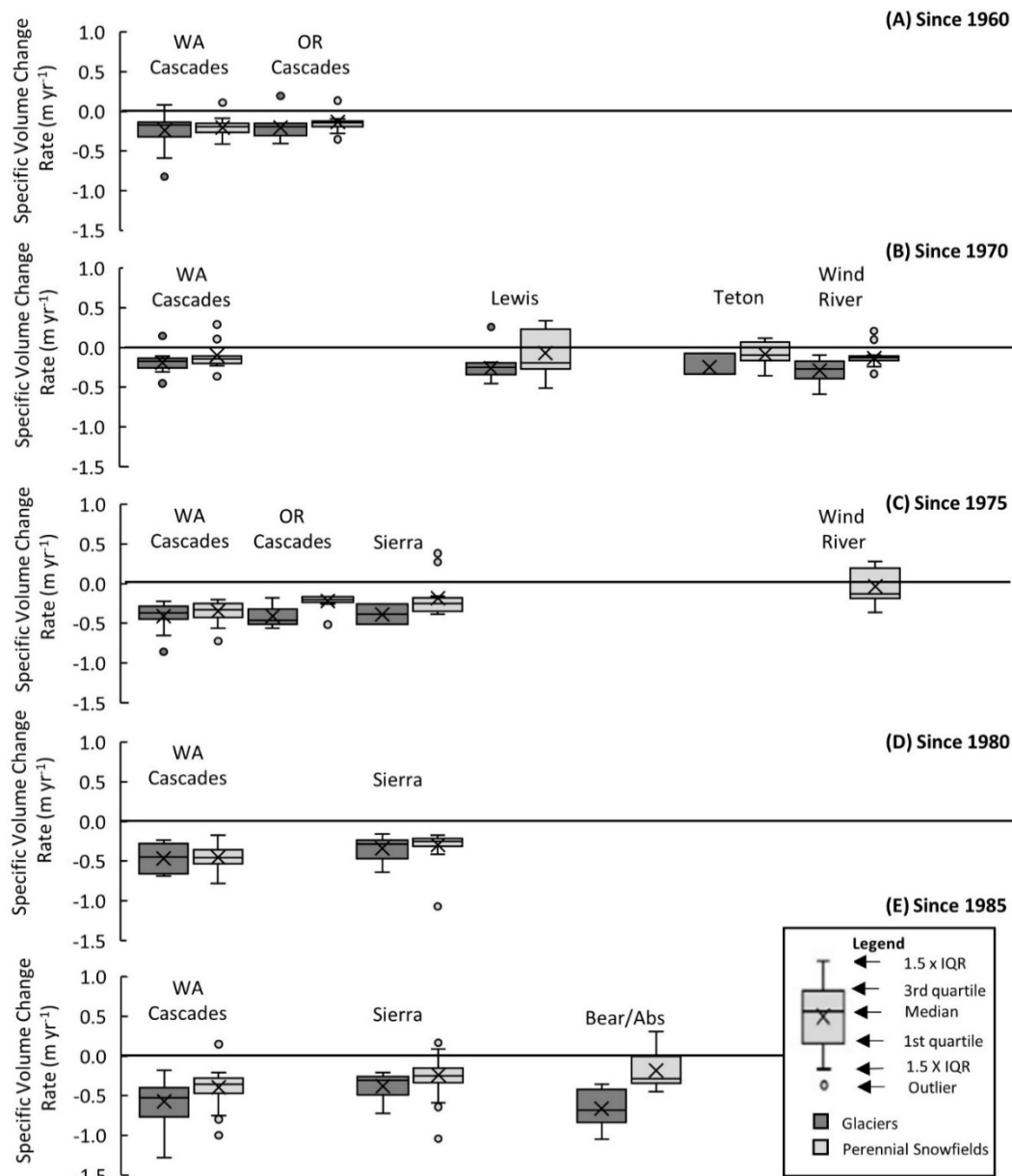


298 **Figure 3.** Specific volume change of glaciers and perennial snowfields (G&PS). Light  
 299 grey circles represent perennial snowfields, and dark grey circles represent glaciers. The  
 300 ‘whiskers’ represent uncertainty. Initial area refers to the area from the U.S. Geological  
 301 Survey’s 1:24000 map series.

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309 **Figure 4.** Volume change glaciers (dark grey boxes) and perennial snowfields (light grey  
310 boxes for each region with more than ten features, grouped by initial mapping date (all  
311 ending in 2016), 1960 (1956 to 1960) (A), 1970 (1966 to 1970) (B), 1975 (1971 to 1975)  
312 (C), 1980 (1976 to 1980) (D), and 1985 (1981 to 1985) (E). The ‘whiskers’ represent the  
313 smallest and largest values not considered outliers. The values that exceed 1.5 times the  
314 interquartile range (IQR) below the first quartile or above the third quartile are  
315 considered outliers (open circles ‘Bear/Abs’ refers to Beartooth-Absaroka, MT.

#### 4. Discussion and Conclusions

GLISTIN was developed for measuring the relatively flat surfaces of large glaciers and ice sheets, and its application to the complex topography alpine terrain presents a stress-case for the instrument. GLISTIN elevation mosaics compared favorably to lidar measurements over barren earth  $+0.17 \pm 1.78$  m (3 m posting). Similar comparisons over bedrock in Greenland showed,  $+0.32 \pm 0.95$  m (30 m posting) for single pass elevations (Moller et al., 2019). Over snow and ice surfaces on Mount Adams the mean difference of GLISTIN and lidar was  $-0.87 \pm 3.8$  m (3 m posting). We regard much of the difference due to snow and ice melt over the 28-day interval between the initial lidar and later GLISTIN surveys. Similar mean GLISTIN – lidar differences, were observed on two gently sloping glacier surfaces in Alaska,  $+0.8 \pm 1.7$  m and  $+1.2 \pm 3.7$  m (3 m posting, Moller et al., 2019). There was a similarly substantial time interval between the GLISTIN and subsequent lidar surveys of 1.5 month and 1 month, respectively. Differencing GLISTIN from the NED for estimating historic glacier change showed the RMSE at control zones to be 7.35 m and largely driven by uncertainty in the NED.

The standard deviations for all elevation comparisons increased with surface slope and most likely due to small offsets in aligning the DEMs. This result is also common to other studies using matching DEMs. The mean elevation difference (Shuttle Radar Topography Mission 1 Arc-Second Global DEM) over non-glaciated terrain near the Akshirak glaciers (Tien Shan, Central Asia) was  $-4.5 \pm 10.9$  m for slopes between  $25^\circ$  and  $30^\circ$ , increasing to  $-7.6 \pm 25.6$  m for slopes between  $40^\circ$  and  $78^\circ$  (Paul, 2008; Surazakov & Aizen, 2006). For North & Middle Sisters, Oregon the RMSE (lidar-NED) was 5.7 m and 12.3 m for slopes between  $20^\circ$  to  $30^\circ$  and  $50^\circ$  to  $60^\circ$ , respectively (Ohlschlager, 2015), and similar to the GLISTIN-NED RMSE of 6.4 m and 10.2 m for the same slope bins.

Elevations were acquired for 85% of the surveyed glaciers and perennial snowfields, of which 12% were completely mapped and 60% had  $\geq 80\%$  coverage. Increased number of

347 flight passes increased data coverage. This is one clear advantage over satellite InSAR  
348 that look direction can be easily changed. Most of the missing backscatter was caused by  
349 radar shadow and some from layover due to the steep terrain.

350

351 Rates of glacier specific mass loss across the western US are consistent with rates  
352 estimated by other studies in our region. Overall, our rates over the last period of our  
353 study 1985 - 2016 are consistent with the western US average (2000-2020) of about -0.4  
354 m yr<sup>-1</sup> (Hugonnet et al., 2021). For the Cascade Range in Washington, Menounos et al.  
355 (2018) estimated  $-0.29 \pm 0.10$  m yr<sup>-1</sup> (2000-2018) from DEMs derived from optical  
356 satellite imagery, which is half of our estimate of  $-0.63 \pm 0.26$  m yr<sup>-1</sup> over the longer time  
357 period of 1985-2016. Furthermore, our historic (pre-2000) rates of change is similar to  
358 rates elsewhere globally (Andreassen et al., 2020; Carturan et al., 2013; DeBEER &  
359 Sharp, 2007; Lambrecht & Kuhn, 2007). We also note an acceleration in mass loss since  
360 1980.

361

362 GLISTIN makes an important contribution in tracking glacier change because data can be  
363 rapidly collected unimpeded by weather providing a near instantaneous elevation survey  
364 of glaciers across broad regions. It performed well in complex terrain exceeding its  
365 design requirement and future improvements in flight planning will reduce the  
366 uncertainty. Significantly improved uncertainty for larger glaciers is expected due to  
367 spatial averaging that reduces the random error component.

368

### 369 **Acknowledgments**

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371 thank Yang Zhen and the GLISTIN group at JPL for their help in data processing and  
372 interpretation.

### 373 **Data Availability Statement**

374 Analyzed data are included as Supporting Information S1. The single radar swaths of  
375 elevation can be obtained from NASA, <https://uavsar.jpl.nasa.gov/cgi-bin/data.pl>, select

TopSAR (Ka-band). The mosaicked radar swaths used in this study can be found at, [https://pdxscholar.library.pdx.edu/geology\\_data/5/](https://pdxscholar.library.pdx.edu/geology_data/5/). The reference glacier outlines and elevations derived from the historic 1:24,000 USGS topographic maps and historic National Elevation Dataset (NED), respectively are located at, [https://pdxscholar.library.pdx.edu/geology\\_data/4/](https://pdxscholar.library.pdx.edu/geology_data/4/).

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## 523 **Supplementary Online Material**

524

525 To identify the date of each glacier DEM, the glacier outlines were combined with a  
526 shapefile of the NED metadata (<https://viewer.nationalmap.gov/basic>) in ArcGIS (ESRI,  
527 Inc.). The NED from non-USGS sources (Table SOM1) did not include metadata for the  
528 imagery date. In those cases, we used the dates listed on the map collars of the USGS  
529 1:24000 topographic maps. Often the same aerial photographs used to create the  
530 topographic maps were also used to derive the NED. Photography used to create the  
531 portion of the NED overlapping the GLISTIN surveys were flown between 1950-1993,  
532 with only two glaciers surveyed in 1950 (Wind River Range, WY) and nine after 1990  
533 (Sierra Nevada, CA). There were 108 glacier outlines where the NED was derived from  
534 imagery spanning multiple years, of which 23 had USGS metadata, clearly identifying  
535 which portion of the outline corresponds with which year. The DEMs covering the  
536 remaining 85 glaciers were from non-USGS sources, and it is unclear what portion of the  
537 glacier were covered by imagery from which year. For G&PS, where multiple images  
538 were used to create the NED, if >80% of the G&PS area was imaged within a single year  
539 (21 G&PS), that year defined the date. For the remaining 64 G&PS, the date is defined as  
540 the average of all years listed. The reported RMSE of the NED (1999 version) is 3.74 m,  
541 but that RMSE under samples high elevation and slopes, fewer than ten samples for slope  
542 > 30°, and ~20 samples for elevations > 3000 m (Gesch, 2007). Therefore, the error over  
543 glaciers and the surrounding alpine environment is probably much higher.

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545 The NED was split into regions corresponding to the mountain ranges covered by  
546 GLISTIN. In some cases, regions were split into smaller sub-regions to reduce processing  
547 time. Each was converted to the same vertical reference system as GLISTIN (WGS84)  
548 using Vdatum then projected into the UTM coordinate system and resampled to 10 m  
549 using bilinear interpolation. The pixel resolution was resampled to 10 m so that it was  
550 standard across all regions. Before resampling, the pixel resolution of the NED differed  
551 by region, ranging from 8.5 m (northern Cascades, WA) to 9.4 m (Sierra Nevada, CA).  
552 GLISTIN was also resampled to 10 m and co-registered to the NED using the methods of

553 Berthier et al. (2007). The co-registration process reduces the horizontal and vertical  
554 offsets between the DEMs by first minimizing the standard deviation of differences over  
555 control zones and then applying that shift to the whole DEM. Offsets between DEMs can  
556 significantly influence estimates of elevation change, particularly on steep slopes  
557 (Berthier et al., 2007).

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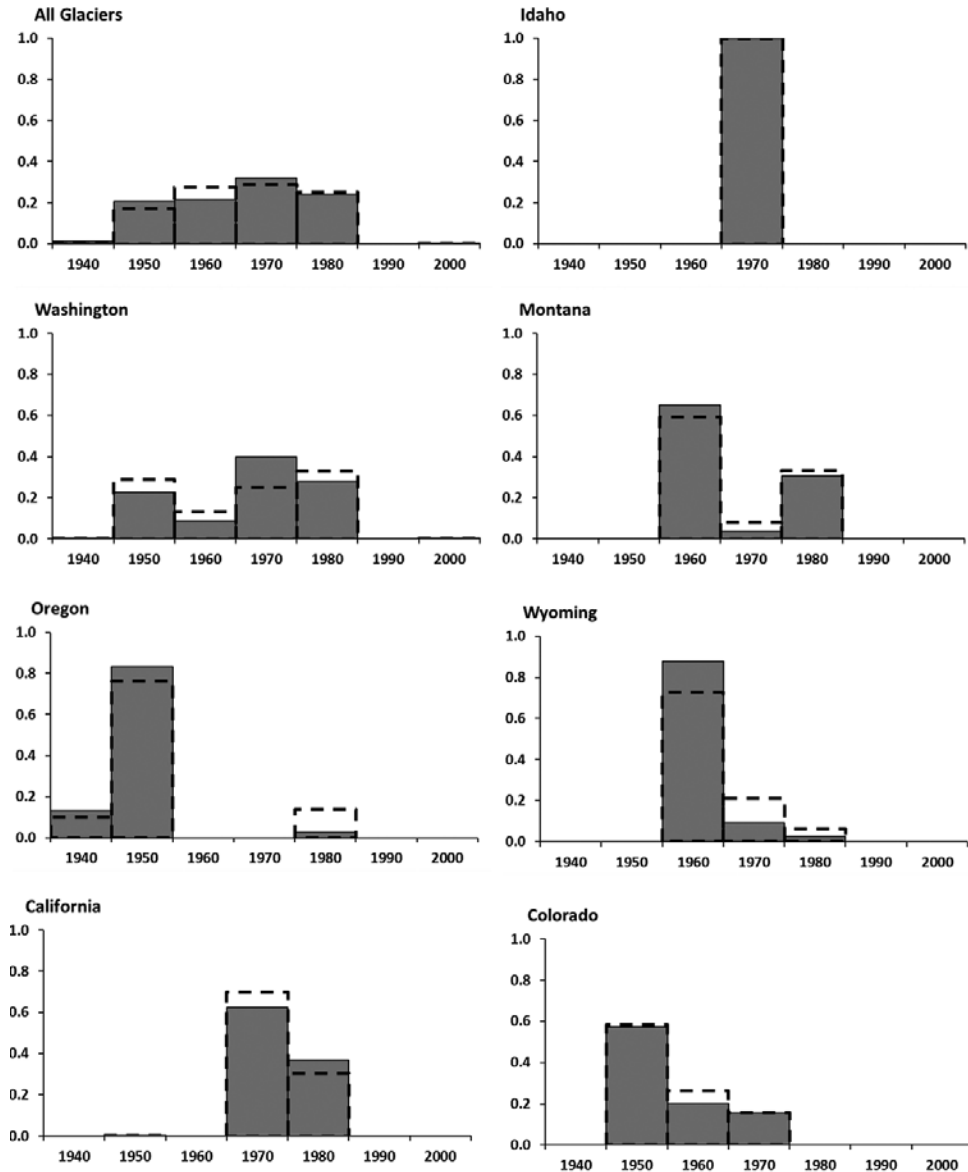
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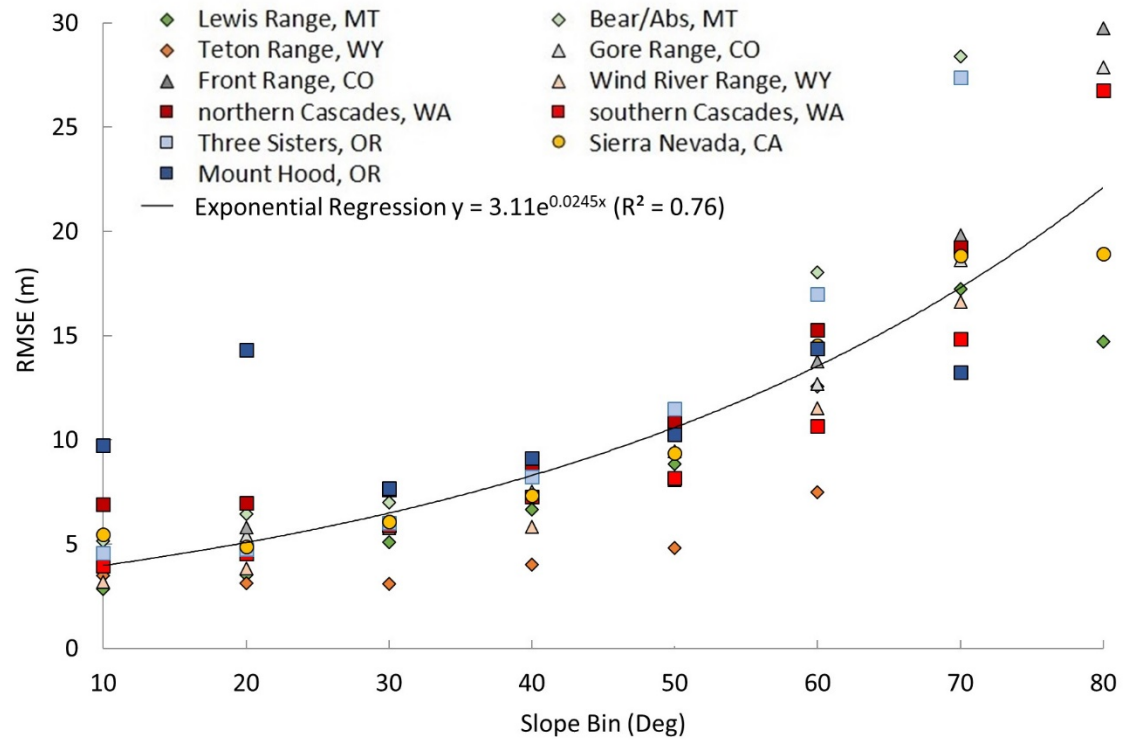
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 569 **Figure SOM1.** Acquisition dates for imagery used to create the U.S. Geological Survey  
 570 1:24000 topographic maps for areas with glaciers and perennial snowfields (G&PS). The  
 571 date on the x-axis represents the full decade (e.g., 1960 = 1960 to 1969). The y-axis is the  
 572 fraction of the total. The solid grey bars are the fraction of area, and the dashed outline is  
 573 the fraction of the number of G&PS. The top left depicts the imagery for all G&PS in the  
 574 western U.S. The other graphs show the acquisition date for each state. Reprinted from  
 575 Fountain et al. (2017).  
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**Figure SOM2.** Root mean square error (RMSE) between GLISTIN elevations and the National Elevation Dataset for control zones binned by 10° slopes. The slope label represents the maximum of that bin. The 10° slope bin includes slopes of 0°.



**Table SOM1.** List of sources compiled for the historical elevation data. The three sources used were the National Map, maintained by the U.S. Geological Survey (USGS), the Oregon office of the Bureau of Land Management (BLM), and the Geomorphological Research Group at the University of Washington (UW).

State/Range	Source	Website
<b>California</b>		
Sierra Nevada	USGS	<a href="https://viewer.nationalmap.gov/basic">https://viewer.nationalmap.gov/basic</a>
<b>Colorado</b>		
Front	USGS	<a href="https://viewer.nationalmap.gov/basic">https://viewer.nationalmap.gov/basic</a>
Gore	USGS	<a href="https://viewer.nationalmap.gov/basic">https://viewer.nationalmap.gov/basic</a>
<b>Montana</b>		
Beartooth-Absaroka	USGS	<a href="https://viewer.nationalmap.gov/basic">https://viewer.nationalmap.gov/basic</a>
Lewis	USGS	<a href="https://viewer.nationalmap.gov/basic">https://viewer.nationalmap.gov/basic</a>
<b>Oregon</b>		
Cascade	BLM	<a href="http://earthexplorer.usgs.gov">http://earthexplorer.usgs.gov</a>
<b>Washington</b>		
northern Cascades	UW	<a href="http://gis.ess.washington.edu/data/">http://gis.ess.washington.edu/data/</a>
northern Cascades	USGS	<a href="https://viewer.nationalmap.gov/basic">https://viewer.nationalmap.gov/basic</a>
southern Cascades	BLM	<a href="http://earthexplorer.usgs.gov">http://earthexplorer.usgs.gov</a>
<b>Wyoming</b>		
Teton	USGS	<a href="https://viewer.nationalmap.gov/basic">https://viewer.nationalmap.gov/basic</a>
Wind River	USGS	<a href="https://viewer.nationalmap.gov/basic">https://viewer.nationalmap.gov/basic</a>

**Table SOM2.** List of lidar datasets used for the absolute error assessment. The datasets came from three sources, the National Map, maintained by the U.S. Geological Survey (USGS; <https://viewer.nationalmap.gov/basic/>), Washington Department of Natural Resources (WA DNR; <https://lidarportal.dnr.wa.gov/>), and Oregon Department of Geology and Mineral Industries (DOGAMI; <https://gis.dogami.oregon.gov/maps/lidarviewer/>). ‘Uncertainty’ refers to the reported absolute vertical uncertainty of the lidar.

Region	Year	Source	Uncertainty
Mount Adams, WA	2016	USGS	0.07
northern Cascade Range, WA	2009	WA DNR	0.04
Mount Rainier, WA	2007/2008	WA DNR	0.04
Three Sisters, OR	2010	DOGAMI	0.04

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**Table SOM3.** Amount of missing data in GLISTIN mosaic based on the number of flight passes. ‘Missing Area’ is the total area of pixels for the listed category in the GLISTIN mosaic that had no elevation data. ‘Total Area’ is the total area of all pixels for the category in the GLISTIN mosaic. ‘% Missing’ is the ratio of the missing area divided by the total area within that category.

Flight Passes	Missing Area (km <sup>2</sup> )	Total Area (km <sup>2</sup> )	% Missing
1	8575.94	10259.58	83.59
2	5368.17	15877.95	33.81
3	1167.58	7344.92	15.90
4	912.02	6511.64	14.01
5	154.29	813.70	18.96
6	51.56	379.55	13.59
7	8.67	147.40	5.88
8	4.00	64.31	6.23

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**Table SOM4.** Elevation uncertainty for control zones estimated from comparing GLISTIN, lidar, and National Elevation Dataset (NED). The sources and accuracy of the lidar data are listed in the supplementary online material. ‘Region’ refers to the region of the mosaicked GLISTIN digital elevation models, ‘Area’ is the area of the control zone, ‘Swath Count’ is a range of the number of GLISTIN flights covering the control zones, and standard deviation, ‘RMSE’ is the root mean square error. The ‘All’ column combines data from the three regions (columns to the left) with multiple GLISTIN passes.

	northern Cascades, WA	Mount Rainier, WA	Three Sisters, OR	All	Mount Adams, WA
Lidar Year	2009	2007/08	2010	---	2016
Area (km <sup>2</sup> )	1.61	3.10	1.95	6.66	12.74
Swath Count	3-6	3-4	2	2-6	1
<b>GLISTIN minus lidar</b>					
RMSE (m)	+1.79	+1.87	+1.64	+1.78	+3.20
Mean $\pm$ std (m)	-0.14 $\pm$ 1.78	+0.38 $\pm$ 1.83	+0.10 $\pm$ 1.63	+0.17 $\pm$ 1.78	0.00 $\pm$ 3.20
Median (m)	-0.08	+0.17	+0.15	+0.11	0.00
<b>GLISTIN minus NED</b>					
RMSE (m)	+8.84	+3.36	+7.14	+6.46	+6.22
Mean $\pm$ std (m)	+4.49 $\pm$ 7.61	+0.57 $\pm$ 3.31	-2.05 $\pm$ 6.84	+1.05 $\pm$ 6.38	+0.49 $\pm$ 6.20
Median (m)	+4.83	+035	-0.49	+0.80	+0.52
<b>Lidar minus NED</b>					
RMSE (m)	+7.21	+2.27	+8.37	+5.89	+5.60
Mean $\pm$ std (m)	+0.13 $\pm$ 7.21	-0.21 $\pm$ 2.27	-2.87 $\pm$ 7.86	-0.89 $\pm$ 5.83	-0.18 $\pm$ 5.60
Median (m)	+0.54	-0.15	-0.62	-0.19	-0.03

647 **Table SOM5.** Root mean square error (RMSE), and mean elevation difference between  
648 the National Elevation Dataset and GLISTIN derived elevations of barren earth control  
649 zones, and total area (Area) of the barren earth control zones in each region sampled.

<b>Region</b>	<b>RMSE (m)</b>	<b>Mean <math>\pm</math> std (m)</b>	<b>Area (km<sup>2</sup>)</b>
northern Cascades, WA	7.74	+0.33 $\pm$ 7.73	107.34
southern Cascades, WA	5.81	+0.62 $\pm$ 5.83	27.06
Mount Hood, OR	8.26	-2.42 $\pm$ 8.25	10.21
Three Sisters, OR	6.07	+0.64 $\pm$ 6.03	23.19
Sierra Nevada, CA	6.64	-1.72 $\pm$ 6.42	191.16
Lewis, MT	8.89	+1.72 $\pm$ 8.80	22.16
Beartooth-Absaroka, MT	10.57	-0.26 $\pm$ 10.57	7.83
Teton, WY	3.53	-0.32 $\pm$ 3.52	0.93
Wind River, WY	6.55	-0.96 $\pm$ 6.48	7.81
Front, CO	8.31	+1.40 $\pm$ 8.19	36.54
Gore, CO	8.15	+1.68 $\pm$ 7.98	27.43
<b>Total</b>	<b>7.32</b>	<b>-0.37 <math>\pm</math> 7.31</b>	<b>461.67</b>

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665 **Table SOM6.** Volume change estimates for glaciers and perennial snowfields in select  
666 regions and periods. Volume change was estimated between the initial NED year and the  
667 GLISTIN year of 2016 for glaciers and perennial snowfields with  $\geq 80\%$  GLISTIN. The  
668 change was grouped by region and year. The year listed is the last in the 5-year interval  
669 (e.g., 1955 = 1951 to 1955). ‘Num’ is the number of G&PS for that category.  
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Region/Year/Type	Num	Area (km <sup>2</sup> )	Volume Change (m <sup>3</sup> x 10 <sup>6</sup> )	Specific Vol Change (m)	Specific Vol Change Rate (m yr <sup>-1</sup> )
<b>WA Cascades</b>					
1960	75	19.70	-336.81 ± 117.49	-17.10 ± 5.96	-0.31 ± 0.11
Glacier	29	17.75	-312.42 ± 106.56	-17.60 ± 6.00	-0.31 ± 0.11
Snowfield	46	1.95	-24.40 ± 10.93	-12.48 ± 5.59	-0.22 ± 0.10
1970	53	53.36	-507.94 ± 255.44	-9.52 ± 4.79	-0.21 ± 0.10
Glacier	23	52.40	-501.59 ± 250.65	-9.57 ± 4.78	-0.21 ± 0.10
Snowfield	30	0.96	-6.35 ± 4.79	-6.62 ± 5.00	-0.14 ± 0.11
1975	82	15.88	-290.34 ± 124.61	-18.29 ± 7.85	-0.45 ± 0.19
Glacier	24	13.14	-249.19 ± 102.35	-18.96 ± 7.79	-0.46 ± 0.19
Snowfield	58	2.73	-41.16 ± 22.26	-15.05 ± 8.14	-0.37 ± 0.20
1980	20	21.40	-320.08 ± 180.75	-14.95 ± 8.44	-0.42 ± 0.23
Glacier	8	20.81	-309.81 ± 175.82	-14.89 ± 8.45	-0.41 ± 0.23
Snowfield	12	0.59	-10.27 ± 4.94	-17.32 ± 8.33	-0.48 ± 0.23
1985	101	34.14	-662.12 ± 275.94	-19.39 ± 8.08	-0.63 ± 0.26
Glacier	40	31.54	-628.40 ± 257.10	-19.92 ± 8.15	-0.64 ± 0.26
Snowfield	61	2.60	-33.71 ± 18.83	-12.97 ± 7.25	-0.42 ± 0.23
<b>OR Cascades</b>					
1960	44	14.47	-215.07 ± 90.29	-14.86 ± 6.24	-0.27 ± 0.11
Glacier	13	12.19	-188.44 ± 76.15	-15.46 ± 6.25	-0.28 ± 0.11
Snowfield	31	2.28	-26.63 ± 14.14	-11.67 ± 6.19	-0.21 ± 0.11
1975	25	8.09	-143.32 ± 50.91	-17.71 ± 6.29	-0.43 ± 0.15
Glacier	9	7.44	-137.50 ± 46.93	-18.48 ± 6.31	-0.45 ± 0.15
Snowfield	16	0.65	-5.83 ± 3.98	-8.97 ± 6.13	-0.22 ± 0.15
<b>Sierra Nevada</b>					
1975	16	0.39	-4.19 ± 2.38	-10.74 ± 6.09	-0.26 ± 0.15
Glacier	2	0.13	-1.85 ± 0.73	-14.57 ± 5.73	-0.36 ± 0.14
Snowfield	14	0.26	-2.35 ± 1.65	-8.90 ± 6.26	-0.22 ± 0.15
1980	35	2.61	-42.98 ± 18.44	-16.44 ± 7.05	-0.46 ± 0.20
Glacier	12	1.95	-34.69 ± 13.74	-17.76 ± 7.04	-0.49 ± 0.20
Snowfield	23	0.66	-8.30 ± 4.70	-12.55 ± 7.10	-0.35 ± 0.20
1985	109	3.87	-40.62 ± 18.78	-10.50 ± 4.86	-0.34 ± 0.16
Glacier	9	1.40	-19.27 ± 8.63	-13.79 ± 6.18	-0.44 ± 0.20
Snowfield	100	2.47	-21.35 ± 10.15	-8.64 ± 4.11	-0.28 ± 0.13
<b>Wind River</b>					
1970	64	23.95	-365.80 ± 115.43	-15.28 ± 4.82	-0.33 ± 0.10
Glacier	19	21.17	-345.41 ± 102.55	-16.31 ± 4.84	-0.35 ± 0.11
Snowfield	45	2.77	-20.40 ± 12.89	-7.35 ± 4.64	-0.16 ± 0.10

1975	24	0.60	$-3.61 \pm$	2.82	$-6.01 \pm 4.70$	$-0.15 \pm 0.11$
Glacier	1	0.05	$-1.12 \pm$	0.27	$-20.90 \pm 4.96$	$-0.51 \pm 0.12$
Snowfield	23	0.55	$-2.49 \pm$	2.56	$-4.55 \pm 4.68$	$-0.11 \pm 0.11$

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