Inventory of glaciers and perennial snowfields of the conterminous USA

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Abstract

This report summarizes an updated inventory of glaciers and perennial snowfields of the conterminous United States. The inventory is based on interpretation of mostly aerial imagery provided by the National Agricultural Imagery Program, U.S. Department of Agriculture with some satellite imagery in places where aerial imagery was not suitable. The inventory includes all perennial snow and ice features ≥ 0.01 km^2. Due to aerial survey schedules and seasonal snow cover, imagery acquired over a number of years were required. The earliest date is 2013 and the latest is 2020, but more than 73% of the outlines were acquired from 2015 imagery. The inventory is compiled as shapefiles within a geographic information system that includes feature classification, area, and location. The inventory identified 1331 (366.52 $\pm$ 14.34 km^2) glaciers, 1776 (31.01 $\pm$ 9.30 km^2) perennial snowfields, and 35 (3.57 km^2 $\pm$ no uncertainty) buried-ice features. The data including both the shapefiles and tabulated results are publicly available at https://doi.org/10.15760/geology-data.03 (Fountain and Glenn, 2022).

1. Introduction

Glaciers are an important feature of the landscape for several reasons. Geologically, they modify the landscape through erosion and deposition (Alley et al., 2019; Benn and Evans, 2010). Although these processes are typically slow, sudden episodes can occur such as moraine failure due to fluvial erosion resulting in catastrophic debris flows (Beason et al., 2018; Chiarle et al., 2007; O'Connor et al., 2001). Hydrologically, glaciers can be viewed as frozen reservoirs of water that naturally regulate streamflow on seasonal to decadal time scales (Dussaillant et al., 2019; Fountain and Tangborn, 1985; Moore et al., 2009). Glacier runoff increases during warm periods and diminishes during cool, wet periods. Thus, glacier populated watersheds have less seasonally variable runoff than ice-free watersheds. Also, glacier runoff cools stream temperatures in the driest and hottest part of the summer after seasonal snowpacks have vanished (Cadbury et al., 2008; Fellman et al., 2014). As glaciers shrink, they have less ability to buffer seasonal runoff variations and watersheds become more susceptible to drought (Huss and Hock, 2018; Pritchard, 2019). Globally, the loss of perennial ice from the landscape is a major contributor to sea level rise (Meier, 1984; Parkes and Marzeion, 2018; Zemp et al., 2019).

Glacier inventories have been valuable for assessing glacier contribution to sea level change (Hock et al., 2009; Pfeffer et al., 2014), and for assessing regional hydrology (Moore et al., 2009; Yao et al., 2007). They also provide a baseline for quantifying future glacier changes. Updated glacier inventories have been compiled for many regions of the world (Andreassen et al., 2022; Bolch et al., 2010; Smiraglia et al., 2015; Sun et al., 2018). An exception has been western

40 United States (US), defined here as those conterminous states west of the 100th meridian. The
41 most recent inventory is (Fountain et al., 2007, 2017) based on U.S. Geological Survey maps
42 compiled over a 40-year period from the late 1940s to the 1980s. Despite a vigorous history of
43 glacier studies (e.g. Armstrong, 1989; Rasmussen, 2009)), glacial geology (e.g. Bowerman and
44 Clark, 2011; Davis, 1988; Osborn et al., 2012)), and regional inventories (e.g. DeVisser and
45 Fountain, 2015; Fagre et al., 2017; Post et al., 1971) the glacier cover for the entire western US
46 has not been reevaluated.

47 The earliest scientific identification of glacier-populated regions in the western US date to King
48 (1871) and, more comprehensively, to Russell (1898). The first summary of glacier-covered area
49 for each state was Meier (1961). However, the data sources and methods used to compile the
50 inventories are unknown. Denton (1975) summarized all known glacier studies in the western US
51 but did not tabulate glacier area. Krimmel (2002) updated Meier's study and provided total
52 glacier area for the various mountain ranges by summarizing a variety previous studies published
53 over a 10+ year time span. It is not clear whether the inventory is complete and no data on
54 individual glaciers are provided. Fountain et al. (2007, 2017) compiled the first comprehensive
55 inventory of glaciers in the western US. The data were derived from historical U.S. Geological
56 Survey (USGS) 1:24,000 scale maps compiled over a 40-year period from the 1940s to the 1980s
57 (Gesch et al., 2002; Usery et al., 2009). Because the USGS mapping was based on one-time
58 aerial imagery, the misinterpretation of seasonal snow as perennial was extensive in some
59 regions. The most current study, Selkowitz & Forster (2016), used Landsat satellite imagery
60 compiled over a four-year period, 2010-2014, and an automated detection scheme to define
61 perennial snow and ice. However, these early automated schemes are known to misclassify
62 debris-covered ice as ice-free landscape underestimating glacier area (Earl and Gardner, 2016;
63 Paul et al., 2007; Rabatel et al., 2017). Recent advances in automated detection have reduced
64 these errors suggesting a more promising future (Lu et al., 2022; Robson et al., 2020).

65 This paper presents the results of an updated and comprehensive inventory of glaciers and
66 perennial snowfields of the western US for the purpose of defining their current extent and to
67 provide of baseline for estimating future changes.   We summarize our methods, uncertainties,
68 tabulated results, and data availability. The data referenced throughout the manuscript are publicly
69 available at https://doi.org/10.15760/geology-data.03.

70 **2. Methods**

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72 2.1 Data Sources, Classification, Digitizing, and Completeness

73 The glaciers and perennial snowfields were initially located using a geographic information
74 system (GIS) database from Fountain et al. (2007, 2017). New outlines were manually digitized
75 from three sources of optical imagery. Most of the outlines were digitized from color digital
76 orthographic aerial photographs available from the National Agricultural Imagery Program
77 (NAIP), U.S. Department of Agriculture, Farm Service Agency program (NAIP, 2017),
78 (https://datagateway.nrcs.usda.gov/GDGHome_DirectDownLoad.aspx). Since 2009, the imagery
79 is collected on cycles of two to three years. The aerial imagery was orthorectified using the
80 inertial navigation system - GPS unit in the aircraft. Photo identifiable GPS-survey ground
81 control points were then used to adjust the photo strip. Orthorectified strips, which had $\geq 30\%$

82   overlap with adjacent strips, were overlaid with each other and with ground control points to
83   check accuracy. The image strips are then mosaicked together. The spatial resolution was ≤ 0.6
84   m with a horizontal accuracy of ≤ 6 m of photo-identifiable ground control points (NAIP, 2017).
85   The NAIP imagery fit the historic USGS glacier outlines remarkably well. In a few cases, NAIP
86   imagery was not suitable due to seasonal snow, deep shadows, or image warping caused by
87   orthophoto rectification, therefore other sources were used including Maxar satellite imagery
88   (Maxar Technologies, Inc) with a spatial resolution of 0.5 – 1 m. For 21 perennial snowfields
89   and three glaciers we relied on the most recent snow-free imagery available in Google Earth
90   (Google, Inc), resolution ~ 1m, because no other imagery was suitable. The outlines were
91   digitized in Google Earth and exported to ArcMap (Esri, Inc).

92   We manually identified all glaciers, ice patches, and perennial snowfields. Glaciers are defined
93   as perennial snow and ice that moves (Cogley et al., 2011). A feature was considered perennial if
94   it was present on the original 1:24,000 USGS topographic maps and present on all Google Earth
95   imagery. Movement was identified by the presence of crevasses. Perennial snowfields and ice
96   patches do not exhibit movement, as indicated by a lack of crevasses observed in the imagery.
97   We do not distinguish between snowfields and ice patches and refer to both as perennial
98   snowfields.

99   Contiguous glacier cover, most commonly on volcanoes, was separated into individual glaciers if
100   they had unique names as indicated on the USGS maps. The orientation of crevasse patterns was
101   used to define flow divides. In the absence of these patterns, shaded relief maps from digital
102   elevation models were used. These models were derived from aerial lidar data, flown under
103   contract to the USGS (Bard, 2017a, b, 2019; Robinson, 2014) or the Oregon Department of
104   Geology and Mineral Industries (DOGAMI, 2011).

105   We encountered a number of challenges to our classification and delineation of the glaciers and
106   perennial snowfields. Although crevasses were used to define movement, in a few cases it
107   appeared that they penetrated through the feature to the bedrock underneath suggesting a
108   mechanical break up. In these cases, the feature was classified as a snowfield. Debris-cover
109   made defining the glacier outline for some glaciers on the volcanoes of the Cascade Range. We
110   relied on local knowledge to help define some boundaries and independent digitization efforts by
111   the authors and others to provide an uncertainty as explained below. In the high alpine regions of
112   California, Colorado, and Wyoming, the terminus of some glaciers was hard to define. Rather
113   than abruptly terminating, the ice seems to thin and smoothly transitions into the surrounding
114   rock talus (Figure 1). It was unclear whether a thin debris layer blanketed the ice or cobbles and
115   boulders protruded through the thin ice. The boundary was mapped along the edge of identifiable
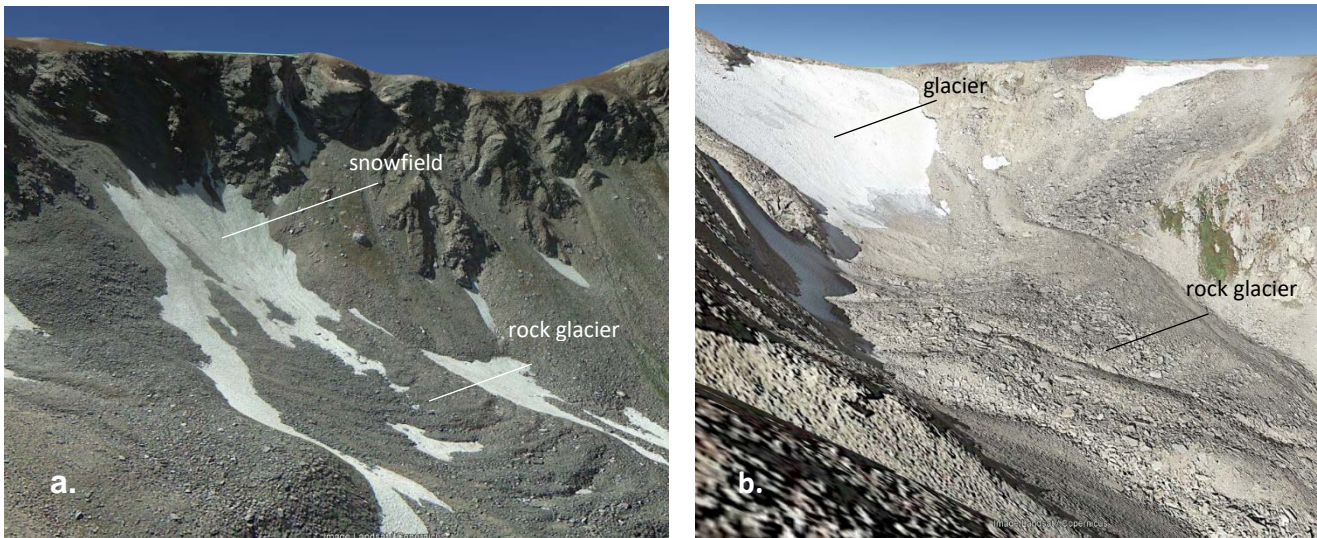116   ice.

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Figure 1. An example of a glacier seemingly melting into the talus surrounding the terminus (upper right). The glacier is flowing from the lower left-hand corner to the upper right-hand corner. The glacier is located in the Wind River Range, WY, INV_ID E618081N4774579 and base image is from the National Agricultural Image Program taken in 2015.

In a few situations, we found it difficult to distinguish glaciers from rock glaciers (Brardinoni et al., 2019). A rock glacier is a mass of rock debris in a matrix of ice that flows (Cogley et al., 2011). They can be difficult to distinguish from a debris-covered glacier, one that has extensive rock debris over the ablation zone, that lower part of a glacier with exposed ice in late summer. We adopted the following topographic classification. If the slope of the apparent ice patch/snowfield was similar to the slope of the rock glacier then we considered it part of the rock glacier (Figure 2a). On the other hand, if a topographic depression separates the apparent glacier/snowfield from the start of a rock glacier, then it was considered independent feature (Figure 2b). This latter case is similar to the "glacier forefield-connected" rock glacier as described by (RGIK, 2022).

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143 In a number of situations, we observed buried ice adjacent to a glacier (Figure 3). Here we use
144 the term 'buried ice' to mean dead ice formerly part of a flowing glacier, and not the permafrost
145 context of ice embedded within or on top of perennially frozen ground. The rocky surface texture
146 of the buried ice was hummocky and very different from surrounding bedrock and adjacent ice,
147 and not a moraine. Occasionally a crack in the surface revealed subsurface ice. The feature
148 appeared to be non-moving (dead) ice that is covered by debris similar to some of the ice-debris
149 complexes described by Bolch et al. (2019). We decided to include these features as a separate
150 classification, 'buried ice', because their size was large relative to the glacier, they were probably
151 once part of the glacier, and may be important local sources of meltwater for streamflow.
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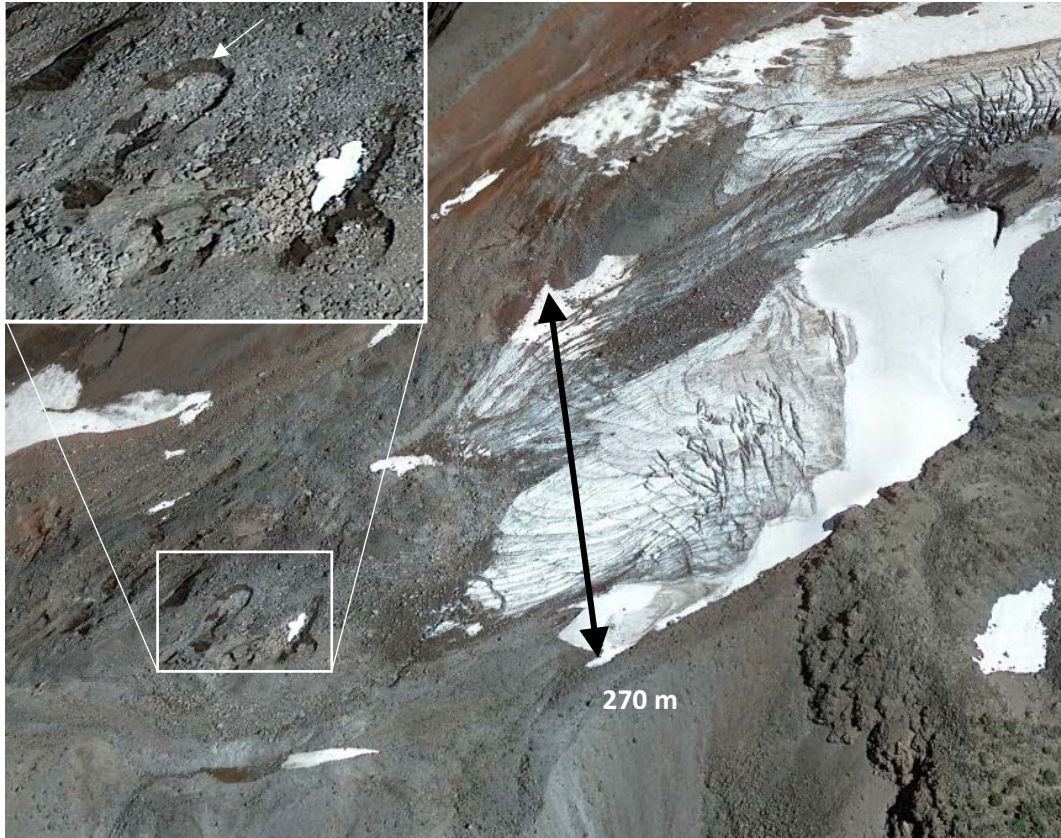
Figure 3. Lost Creek Glacier, South Sister, Oregon. Note buried ice and lack of crevasses to the left of the grey-blue ice, suggesting ice that is no longer moving and therefore not part of the dynamic glacier. The white box surrounds an area that has collapsed due to subsurface melt. The inset enlargement shows a cliff edge of exposed dirty ice (white arrow in upper left) indicated by a darker color suggesting wet sediment and a finer texture than the surface debris. The black arrow shows the width of the cleaner ice for scale. Image is from © Google Earth, 8/9/2021.

The glaciers and perennial snowfields outlines were digitized using ArcMap (Esri, Inc), a geographic information system, at scales varying from 1:300 to 1:2000 depending on image quality and complexity. We used the native projection of the image, North American Datum of 1983 (NAD83) for NAIP, and World Geodetic System 1984 (WGS84) for Maxar and Google Earth. When Maxar or Google Earth imagery were used, final outlines were projected into the NAD83 coordinate system. Google Earth was often used an additional aid in interpretation because of its tilt and rotation features yielded oblique perspectives. Retaining only those outlines ≥ 0.01 km^2, each was checked independently by the two senior authors of this report and in some cases by a third collaborator in order to reduce bias (Leigh et al., 2019). If an outline was revised, then it was returned to its original author for review and correction, and the process iterated until all parties agreed.

Our initial inventory was then compared sequentially to two other independent inventories to test for errors of omission or commission. The first comparison was to the Selkowitz and Forster (2016) inventory (SFI). However, to compare the inventories we had to first reconcile the

179 differences in methods. Buried-ice features were eliminated from our inventory because the SFI
180 did not map buried ice. The SFI was filtered to only include features ≥ 0.01 km^2 to match our
181 minimum area threshold; a small number of features located in Canada were removed; and a few
182 mis-classifications of ponds, lakes and dry lakebeds as glaciers were removed. Notably, the SFI
183 did not split contiguous ice masses, such as glacier-covered volcanoes, into individual glaciers,
184 consequently we do not expect the number of features in the SFI and our inventory to match.
185 Once the two inventories were reconciled, those glaciers and perennial snowfields unique to one
186 inventory were examined for inclusion in a revised inventory. Features selected from the SFI
187 were digitized using the same imagery we used for our inventory.
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189 The revised inventory was then compared to the 2016 National Land Cover Database
190 (NLCD(Dewitz, 2019), which did not map glaciers and perennial snowfields per se, but mapped
191 the distribution of perennial snow and ice (Jin et al., 2019; Wickham et al., 2021). However, the
192 NLCD used a small number of recent images to assess a 'perennial' presence and therefore
193 significant errors of commission are expected. Also, the landscape class of snow and ice received
194 less attention than other classes (e.g. agriculture) such that the timing of imagery acquisition may
195 be earlier in the summer than optimal and misclassification of clouds as snow and ice may be
196 present (personal communication C. Homer and J. Dewitz, USGS, email December 2015). The
197 NLCD inventory was compared to the revised inventory and, as before, the features unique to
198 one inventory were examined for inclusion. Those features selected from the NLCD for inclusion
199 were digitized using the same imagery we used for our inventory.
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201 2.2 Uncertainty
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203 Three main sources of uncertainty in the glacier outlines, are georeferencing, digitization, and
204 interpretation (DeVisser and Fountain, 2015; Sitts et al., 2010). We found georeferencing error to
205 very small. In any case, the precise location of the outline does not affect its area. Also, the
206 digitized points are highly correlated such that no deviations from the true outline are caused by
207 georeferencing. Digitizing error is relatively small, 1%, with good imagery and crisp contrast
208 between the glacier and ice-free surroundings (DeVisser and Fountain, 2015; Hoffman et al.,
209 2007). The largest uncertainty is interpretation error caused by poor imagery, shadow, debris
210 cover, and seasonal snow patches. This uncertainty was calculated in different ways according to
211 the situation. If the outline was digitized a second (or third) time due different interpretations by
212 the authors or collaborators the uncertainty is one-half the absolute difference of the between the
213 largest and smallest digitized areas (the range) divided by the final area and expressed as a
214 percentage. For the relatively few glaciers where a small section of perimeter was masked by
215 deep shadow, seasonal snow patches, rock debris, or poor imagery, a higher uncertainty was
216 assigned by visually estimating the area in question and dividing by the total possible area. In a
217 few cases the location of a flow divide between glaciers wasn't clear a 5% error is assigned. This
218 was calculated from the area difference in several test cases where multiple possible flow divides
219 were digitized. For perennial snowfields, the smaller patch of perennial snow is often covered by
220 seasonal snow, which varies greatly from year to year. We measured the area of a number of
221 snowfields over time using late summer historic imagery in Google Earth. Results showed that
222 the variations in snowfield area could be as much as 30%. We assigned this somewhat arbitrary
223 uncertainty in order to note snowfield presence and location, but preclude them from area change
224 calculations because area differences are typically smaller than the assigned uncertainty.

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3. Results

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228 Our initial inventory identified 2267 glaciers and perennial snowfields totaling 391.95 km^2.
229 About 70% (1576) overlapped the features in the SFI. After examining all features unique to
230 each inventory, we revised our inventory to include 2373 (394.99 km^2) glaciers and perennial
231 snowfields. Comparing the revised inventory to the 2016 NLCD resulted in adding another 134
232 (2.53 km^2) features, which included 12 (0.38 km^2) glaciers. The final inventory includes 2542
233 features composed of 1331 (366.52 km^2) glaciers, 1176 (31.01 km^2) perennial snowfields, and 35
234 (3.57 km^2) buried ice deposits (Table 1; Figure 4). Most glaciers and perennial snowfields, 1554
235 (62%) were outlined using 2015 NAIP imagery with the remainder outlined using mostly NAIP
236 imagery from 2013 to 2020.

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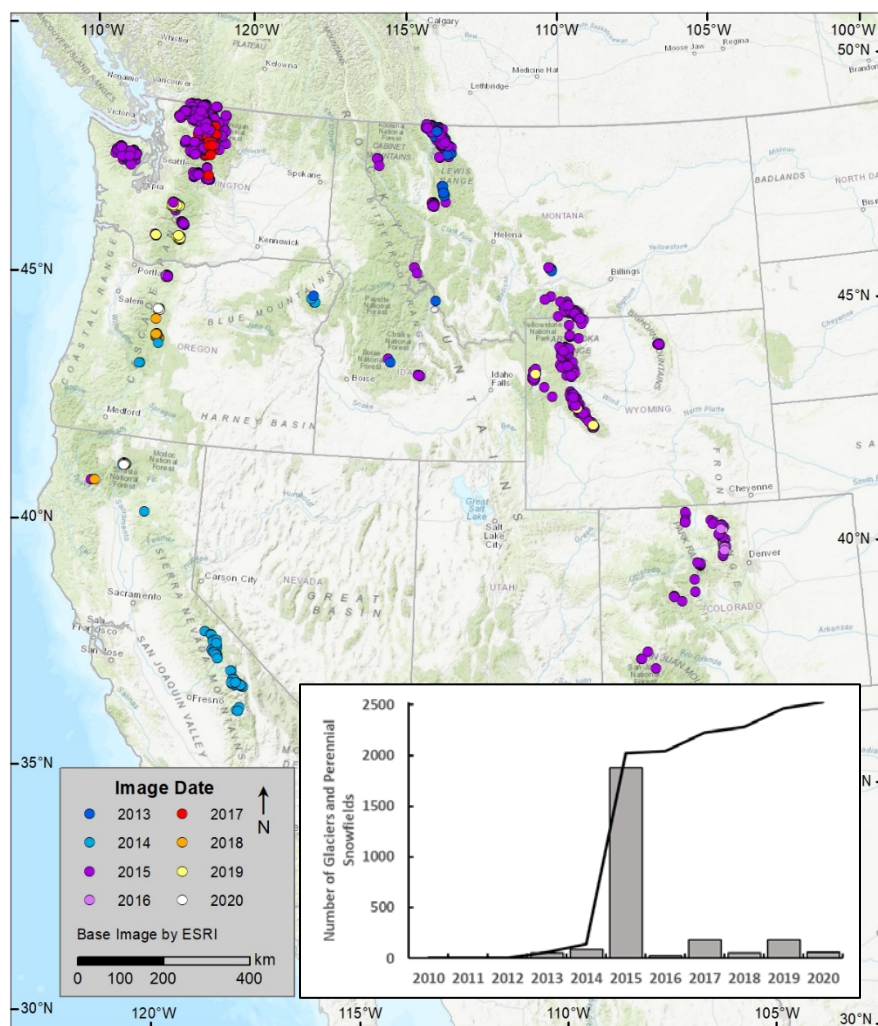
Figure 4. The spatial distribution and number of glaciers and perennial snowfields, greater than 0.01 km^2, in the western United States. Colors indicate the date of aerial and satellite imagery used to outline the features. The line is the cumulative total. Base imagery from Esri Inc. Inset is a bar graph and cumulative sum of the number of glaciers and perennial snowfields digitized in each image date.

Table 1. The summary of the glacier inventory for the American West, exclusive of Alaska. Number is the total number of features within each classification (Class), 'Max Area' is the largest area of the feature within that class and 'Mean Area' is the average area. Note that the uncertainty of 'Buried ice' is unknown.

State/Region/Class	Number	Total Area km^2	Max Area km^2	Mean Area km^2
California	**132**	**10.63 ± 0.61**	**1.45**	**0.08**
Cascade Range	**39**	**5.74 ± 0.37**	**1.45**	**0.15**
Buried ice	5	0.44	0.16	0.09
Glaciers	10	4.61 ± 0.17	1.45	0.46
Perennial snowfields	24	0.68 ± 0.21	0.08	0.03
Sierra Nevada	**91**	**4.86 ± 0.23**	**0.66**	**0.05**
Buried ice	2	0.13	0.10	0.06
Glaciers	64	4.37 ± 0.12	0.66	0.07
Perennial snowfields	25	0.37 ± 0.11	0.03	0.01
Trinity Alps	**2**	**0.03 ± 0.00**	**0.02**	**0.02**
Glaciers	2	0.03 ± 0.00	0.02	0.02
Colorado	**84**	**2.20 ± 0.46**	**0.16**	**0.03**
Elk Mountains	**5**	**0.09 ± 0.03**	**0.03**	**0.02**
Glaciers	1	0.01 ± 0.00	0.01	0.01
Perennial snowfields	4	0.08 ± 0.02	0.03	0.02
Front Range	**58**	**1.73 ± 0.33**	**0.16**	**0.03**
Glaciers	13	0.74 ± 0.03	0.16	0.06
Perennial snowfields	45	0.99 ± 0.30	0.09	0.02
Gore Range	**7**	**0.11 ± 0.03**	**0.02**	**0.02**
Glaciers	1	0.02 ± 0.00	0.02	0.02
Perennial snowfields	6	0.09 ± 0.03	0.02	0.02
Medicine Bow Mountains	**1**	**0.04 ± 0.01**	**0.04**	**0.04**
Perennial snowfields	1	0.04 ± 0.01	0.04	0.04
Park Range	**6**	**0.11 ± 0.03**	**0.03**	**0.02**
Perennial snowfields	6	0.11 ± 0.03	0.03	0.02
San Miguel Mountains	**5**	**0.07 ± 0.02**	**0.02**	**0.01**
Perennial snowfields	5	0.07 ± 0.02	0.02	0.01
Sawatch Range	**2**	**0.04 ± 0.01**	**0.03**	**0.02**
Perennial snowfields	2	0.04 ± 0.01	0.03	0.02
Idaho	**6**	**0.08 ± 0.02**	**0.02**	**0.01**
Sawtooth Range	**6**	**0.08 ± 0.02**	**0.02**	**0.01**

Perennial snowfields	6	0.08 ± 0.02	0.02	0.01
Montana	**416**	**30.26 ± 2.27**	**1.45**	**0.07**
Beartooth -Absaroka	**111**	**6.07 ± 0.64**	**0.45**	**0.05**
Buried ice	1	0.04	0.04	0.04
Glaciers	50	4.31 ± 0.12	0.45	0.09
Perennial snowfields	60	1.72 ± 0.52	0.22	0.03
Bitterroot Range	**4**	**0.08 ± 0.02**	**0.03**	**0.02**
Glaciers	1	0.03 ± 0.00	0.03	0.03
Perennial snowfields	3	0.05 ± 0.02	0.02	0.02
Cabinet Mountains	**9**	**0.25 ± 0.08**	**0.08**	**0.03**
Perennial snowfields	9	0.25 ± 0.08	0.08	0.03
Crazy Mountains	**13**	**0.27 ± 0.06**	**0.04**	**0.02**
Glaciers	3	0.06 ± 0.00	0.04	0.02
Perennial snowfields	10	0.21 ± 0.06	0.04	0.02
Lewis Range	**230**	**21.38 ± 1.15**	**1.45**	**0.09**
Glaciers	145	19.22 ± 0.50	1.45	0.13
Perennial snowfields	85	2.16 ± 0.65	0.09	0.03
Mission-Swan-Flathead	**49**	**2.20 ± 0.34**	**0.22**	**0.04**
Glaciers	11	1.16 ± 0.02	0.22	0.11
Perennial snowfields	38	1.04 ± 0.31	0.09	0.03
Oregon	**116**	**15.38 ± 1.62**	**1.16**	**0.13**
Cascade Range	**110**	**15.24 ± 1.58**	**1.16**	**0.14**
Buried ice	7	1.25	0.45	0.18
Glaciers	42	11.90 ± 0.95	1.16	0.28
Perennial snowfields	61	2.09 ± 0.63	0.15	0.03
Wallowa Mountains	**6**	**0.14 ± 0.63**	**0.04**	**0.02**
Perennial snowfields	6	0.14 ± 0.04	0.04	0.02
Washington	**1481**	**312.26 ± 16.33**	**11.24**	**0.21**
Cascade Range-Northern	**1126**	**186.58 ± 9.64**	**6.06**	**0.17**
Buried ice	10	0.50	0.15	0.05
Glaciers	706	176.27 ± 6.70	6.06	0.25
Perennial snowfields	410	9.80 ± 2.94	0.16	0.02
Cascade Range-Southern	**219**	**101.66 ± 5.86**	**11.24**	**0.46**
Buried ice	10	1.20	0.30	0.12
Glaciers	69	95.64 ± 4.42	11.24	1.39
Perennial snowfields	140	4.82 ± 1.45	0.33	0.03
Olympic Mountains	**136**	**24.02 ± 0.82**	**5.09**	**0.18**
Glacier	106	23.44 ± 0.65	5.09	0.22
Perennial snowfield	30	0.57 ± 0.17	0.06	0.02
Wyoming	**307**	**30.29 ± 2.34**	**2.32**	**0.10**
Absaroka Range	**62**	**1.44 ± 0.33**	**0.12**	**0.02**
Glacier	10	0.48 ± 0.05	0.12	0.05
Perennial snowfield	52	0.96 ± 0.29	0.05	0.02
Bighorn Mountains	**8**	**0.42 ± 0.03**	**0.22**	**0.05**
Glacier	3	0.34 ± 0.01	0.22	0.11

Perennial snowfield	5	0.08 ± 0.02	0.03	0.02
Teton Range	**49**	**2.04 ± 0.21**	**0.23**	**0.04**
Glacier	20	1.46 ± 0.03	0.23	0.07
Perennial snowfield	29	0.59 ± 0.18	0.05	0.02
Wind River Range	**188**	**26.39 ± 1.76**	**2.32**	**0.14**
Glacier	74	22.42 ± 0.57	2.32	0.30
Perennial snowfield	114	3.97 ± 1.19	0.26	0.03
Grand Total	**2542**	**401.10 ± 23.64**	**11.24**	**0.16**

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252 Before summarizing the inventory data, a note about the content in Appendix A. It summarizes
253 the officially named glaciers that we regard as snowfields or missing; labeling issues found in the
254 USGS Geographic Names Information System, the official agency responsible for hosting the
255 names and locations of landscape features; and detailed notes, organized by US State, on the
256 specific imagery used and challenges encountered digitizing glacier and snowfield outlines.

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258 The glaciers and perennial snowfields are generally small, averaging 0.28 and 0.03 km^2,
259 respectively. Like glaciers elsewhere in the northern hemisphere, most glaciers face north to east.
260 (Evans, 2006; Fountain et al., 2017; Schiefer et al., 2007). The distribution of glacier area is
261 skewed toward smaller ice masses (Figure 5a). The State of Washington in the Pacific Northwest
262 has the largest number of glaciers, ice area and the largest glacier (11.24 km^2 Emmons Glacier)
263 of any of the other states (Table 1). Indeed, the glacier cover on Mount Rainier alone (77.37 km^2)
264 is greater than the total sum in all the other states (71.16 km^2). The elevation distribution of
265 glacier-covered area is bimodal with maxima at 2400 m and 3650 m (Figure 5b). The spatial
266 distribution of elevations shows a regional climate control with the lowest glaciers and perennial
267 snowfields in the maritime climate of the Pacific Northwest of Washington, Oregon, northern
268 California, and western Montana and the high elevations located in the continental climate of
269 central California, Colorado, Wyoming and southern Montana (Figure 6).

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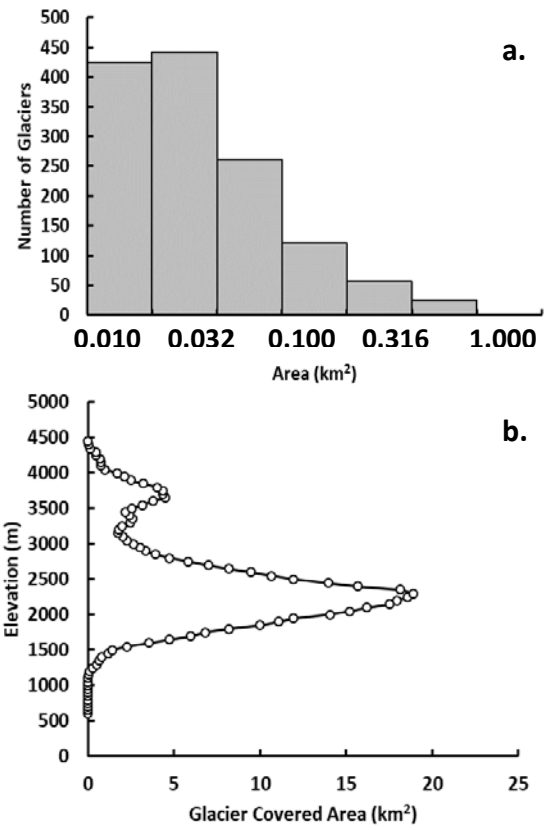
Figure 5. The area and elevation distribution of glaciers in the western U.S., (a) Histogram
showing the number of glaciers as a function of area. The x-axis intervals are log intervals; (b)
Elevation distribution of glacier-covered area.

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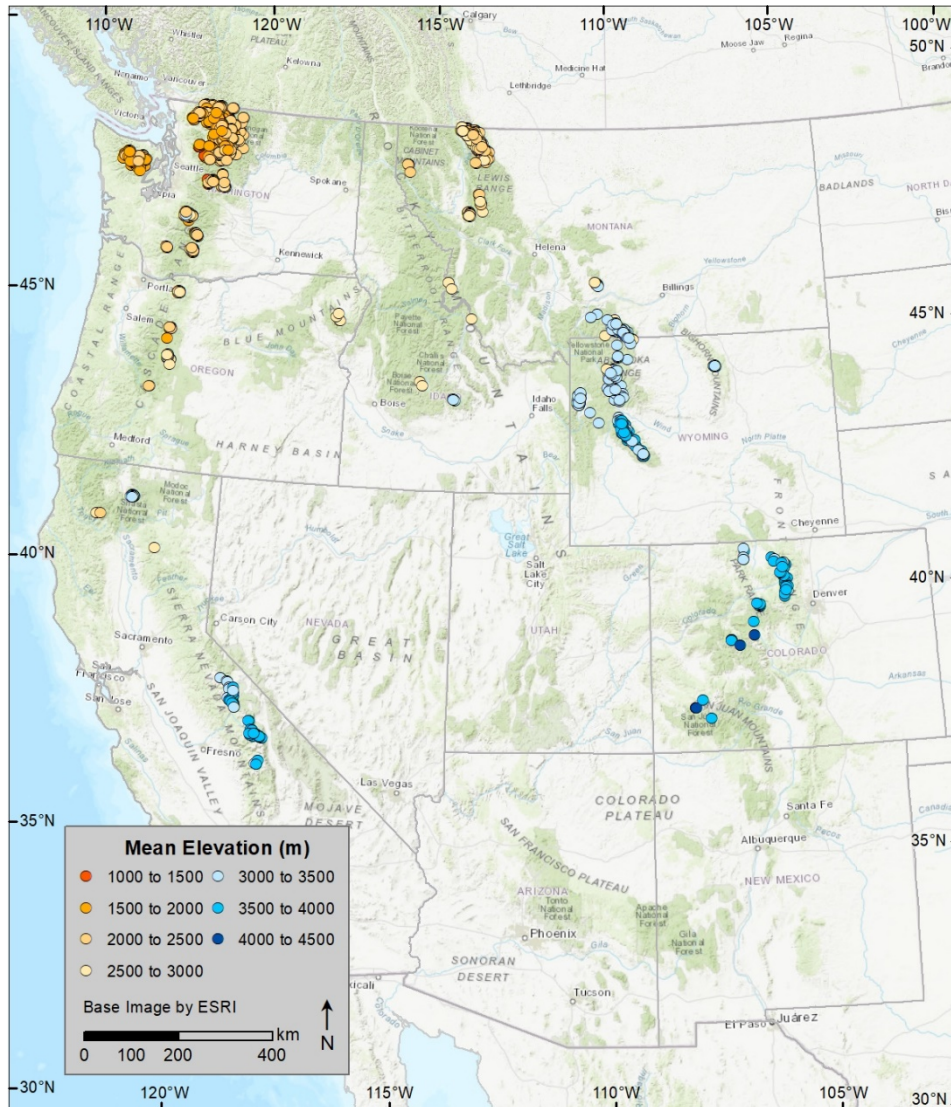
Figure 6. Elevation distribution of glaciers and perennial snowfields across the western US. Base
imagery from Esri Inc.

The final inventory conflicts with the current database of the Geographic Names Information
System (https://www.usgs.gov/us-board-on-geographic-names/domestic-names). The inventory
excludes 52 officially named glaciers because 2 have disappeared, 25 were classified as
perennial snowfields, the area of 18 was less than 0.01 km^2, and 7 were considered rock glaciers
(Appendix A,Table A1). In some cases, a named glacier or snowfield had split into multiple
pieces since the original USGS mapping; all pieces were assigned the same name in the
inventory (Appendix A, Table A2). Several labels that identify the name of the glacier are not
clearly associated with a specific glacier and these are listed in Table 7.3.

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292 **4. Discussion**
293
294 The advent of relatively frequent high resolution ($\leq$ 1 m) optical aerial and satellite imagery
295 available at little or no cost has made compiling and updating glacier inventories a realistic
296 opportunity. Finding suitable imagery spanning only a few years apart provides a near-snapshot
297 of glacier cover. This contrasts strongly with mapping efforts only a few decades ago when
298 aerial-only photographic surveys required decades to cover the western US (Gesch et al., 2002).
299 And the advent of GIS software made digitizing, summarizing, and interrogating digital outlines
300 practical.
301
302 We had used the Fountain et al., 2017 historic inventory as a template to locate and update the
303 perimeters of all the glaciers and perennial snowfields. Considering that the inventory was
304 derived from the U.S. Geological Survey 1:24,000 maps, a result of a national effort to remap the
305 entire country at a higher resolution, we were a surprised that 240 features (~10%) were missed.
306 These missing features were revealed after comparison with two other independently derived
307 inventories. We had a similar experience in a prior study when comparing two independently
308 derived glacier inventories. Together they suggest that independent efforts are important to
309 compiling a comprehensive inventory.
310
311 Multiple checks more accurately define glacier perimeters (Leigh et al., 2019). Different
312 investigators may make different decisions about glacier boundaries and results can differ
313 particularly in debris-covered conditions or along flow divides (Paul et al., 2013). When they
314 agree, it provides some confidence of the interpretation accuracy and where they disagree it
315 provides input for estimating interpretation error.
316
317 The total area of glaciers in the western US, 367 km^2, is a little smaller than that in Austria, 415
318 km^2, (Fischer et al., 2015). Like glacier populated regions elsewhere the distribution of glacier
319 area is skewed towards smaller glaciers (e.g. Linsbauer et al., 2012; Mishra et al., 2023; Zalazar
320 et al., 2020). The uncertainty in glacier area is also similar with an overall 5% uncertainty for the
321 total area. Paul et al. (2020) report an uncertainty of 3.3% over a set of 15 glaciers, 4% for 7
322 glaciers (Zalazar et al., 2020), 2.3% for 15 glaciers (Linsbauer et al., 2021). Our assessment
323 method differs from those cited here in that we estimate the uncertainty for each individual
324 glacier rather than upscaling the uncertainty calculated for a small subsample.
325
326 **5. Data products and availability**
327
328 The data are available in three formats. The geospatial data and attribute tables are available in
329 the shapefile (Esri) format and in an open source GeoJSON format. The attribute table is also
330 available as an EXCEL file. These data products can be obtained from
331 https://doi.org/10.15760/geology-data.03 (Fountain and Glenn, 2022) and from the Global Land
332 Ice Measurements from Space website http://glims.colorado.edu/glacierdata/. Maxar imagery
333 was accessed through the USGS and NGA NEXTVIEW license. The Maxar imagery has limited
334 availability owing to restrictions (proprietary interest). Contact cmcneil@usgs.gov for more

14

335 information.
336
6. Conclusions

339 We have compiled a new and comprehensive inventory of glaciers and perennial snowfields in
340 the western US from aerial and satellite imagery. Results show that 2542 features are currently
341 present and include 1331 (366.52 km^2) glaciers, 1176 (31.01 km^2) perennial snowfields, and 35
342 (3.57 km^2) buried ice deposits. Most of the data were acquired from 2015 NAIP imagery with the
343 remainder from NAIP imagery and a few satellite images acquired over the period of 2013 to
344 2020. The state of Washington has the greatest number and area of glaciers and perennial
345 snowfields. This product updates an older inventory based on USGS 1:24000 maps compiled in
346 the middle-late 1900's. The new inventory is a significant improvement in accuracy because the
347 archive of historical imagery in Google Earth greatly aided our efforts to classify glaciers versus
348 perennial snowfields. Finally, this new inventory provides a baseline for assessing glacier change
349 in the coterminous US.
350
7. Appendix A
352
A1 Missing Glaciers

354 **Table A1** List of officially named glaciers not classified as glaciers and excluded from the final
355 inventory. Names come from the Geographic Names Information System, (US Geological
356 Survey, 2022). The 'Reason' column lists why the named glacier is no longer considered a glacier
357 in our inventory.
358

State/Region/Glacier Name	Reason
California	
Sierra Nevada	
Matthes Glaciers	rock glacier
Mount Warlow Glacier	rock glacier
Powell Glacier	rock glacier
Colorado	
Front Range	
Isabelle Glacier	perennial snowfield
Mills Glacier	perennial snowfield
Moomaw Glacier	perennial snowfield
Peck Glacier	perennial snowfield
Rowe Glacier	< 0.01 km^2
Saint Marys Glacier	< 0.01 km^2
Taylor Glacier	rock glacier
The Dove	< 0.01 km^2
Idaho	
Lost River Range	
Borah Glacier	rock glacier
Montana	

Beartooth Mountains-Absaroka Range

Grasshopper Glacier — rock glacier

Cabinet Mountains

Blackwell Glacier — perennial snowfield

Crazy Mountains

Grasshopper Glacier — rock glacier

Lewis Range

Boulder Glacier — perennial snowfield

Mission-Swan-Flathead Ranges

Fissure Glacier — < 0.01 km^2

Gray Wolf Glacier — perennial snowfield

Oregon

Cascade Range

Carver Glacier — perennial snowfield

Clark Glacier — perennial snowfield

Irving Glacier — perennial snowfield

Lathrop Glacier — < 0.01 km^2

Palmer Glacier — perennial snowfield

Skinner Glacier — perennial snowfield

Thayer Glacier — < 0.01 km^2

Wallowa Mountains

Benson Glacier — perennial snowfield

Washington

Cascade Range-Northern

Lyall Glacier — perennial snowfield

Milk Lake Glacier — disappeared

Snow Creek Glacier — perennial snowfield

Spider Glacier — perennial snowfield

Table Mountain Glacier — < 0.01 km^2

Cascade Range-Southern

Ape Glacier — < 0.01 km^2

Dryer Glacier — perennial snowfield

Forsyth Glacier — < 0.01 km^2

Meade Glacier — perennial snowfield

Nelson Glacier — < 0.01 km^2

Packwood Glacier — perennial snowfield

Pinnacle Glacier — < 0.01 km^2

Pyramid Glaciers — < 0.01 km^2

Shoestring Glacier — < 0.01 km^2

Stevens Glacier — perennial snowfield

Talus Glacier — perennial snowfield

Unicorn Glacier — < 0.01 km^2

Williwakas Glacier — perennial snowfield

Olympic Mountains

Anderson Glacier — perennial snowfield

Lillian Glacier	< 0.01 km^2

Wyoming	
Absaroka Range	
DuNoir Glacier	< 0.01 km^2
Teton Range	
Petersen Glacier	< 0.01 km^2
Teepe Glacier	perennial snowfield
Wind River Range	
Hooker Glacier	disappeared
Harrower Glacier	perennial snowfield
Tiny Glacier	< 0.01 km^2

359

360

A2 Glaciers that have split into multiple pieces and current errors in glacier label names

362

Table A2. List of named glaciers that have split into multiple pieces. Names come from the Geographic Names Information System (https://www.usgs.gov/tools/geographic-names-information-system-gnis). 'Count' refers to the number of pieces in the updated inventory. 'Classes' is the classification of the pieces; glacier, perennial snowfield, buried-ice, or a combination.

State/Region/Glacier Name	Count	Classes
California		
Cascade Range		
Bolam Glacier	2	Glaciers and perennial snowfields
Hotlum Glacier	2	Glaciers and perennial snowfields
Whitney Glacier	2	Glaciers and perennial snowfields
Wintun Glacier	3	Glaciers and perennial snowfields
Sierra Nevada		
Goethe Glacier	2	Glaciers only
Lyell Glacier	4	Glaciers and perennial snowfields
Norman Clyde Glacier	3	Glaciers only
Powell Glacier	2	Glacier and Buried-ice
Colorado		
Front Range		
Saint Vrain Glaciers	6	Glaciers and perennial snowfields
Montana		
Beartooth Mountains-Absaroka Range		
Castle Rock Glacier	3	Glaciers and perennial snowfields
Granite Glacier	2	Glaciers only
Grasshopper Glacier	4	Glaciers and perennial snowfields
Hopper Glacier	2	Glaciers and perennial snowfields
Snowbank Glacier	2	Glaciers only
Wolf Glacier	2	Glaciers only
Lewis Range		
Agassiz Glacier	3	Glaciers only
Blackfoot Glacier	2	Glaciers only

Carter Glaciers	2	Glaciers and perennial snowfields
Dixon Glacier	3	Glaciers and perennial snowfields
Harrison Glacier	5	Glaciers and perennial snowfields
Kintla Glacier	2	Glaciers only
Logan Glacier	2	Glaciers only
Shepard Glacier	3	Glaciers only
Siyeh Glacier	2	Glaciers only
Two Ocean Glacier	2	Glaciers only
Whitecrow Glacier	5	Glaciers and perennial snowfields

Mission Range-Swan Range-Flathead Range

Swan Glaciers	3	Glaciers and perennial snowfields

Oregon

Cascade Range

Bend Glacier	3	Glaciers and perennial snowfields
Clark Glacier	2	Perennial snowfields only
Collier Glacier	2	Glaciers only
Diller Glacier	2	Glaciers and perennial snowfields
Glisan Glacier	2	Glaciers and perennial snowfields
Ladd Glacier	4	Glaciers and perennial snowfields
Langille Glacier	5	Glaciers and perennial snowfields
Newton Clark Glacier	3	Glaciers and perennial snowfields
Palmer Glacier	2	Perennial snowfields only
Prouty Glacier	3	Glaciers and perennial snowfields
Renfrew Glacier	2	Glaciers and perennial snowfields
Russell Glacier	2	Glaciers only
Sandy Glacier	4	Glaciers and perennial snowfields
Skinner Glacier	4	Perennial snowfields only
Waldo Glacier	3	Glaciers only
White River Glacier	2	Glaciers and perennial snowfields
Whitewater Glacier	3	Glaciers only
Zigzag Glacier	3	Glaciers and perennial snowfields

Washington

Cascade Range-Northern

Borealis Glacier	4	Glaciers only
Buckner Glacier	2	Glaciers only
Butterfly Glacier	4	Glaciers only
Colchuck Glacier	2	Glaciers only
Company Glacier	3	Glaciers only
Cool Glacier	2	Glaciers and perennial snowfields
Dana Glacier	3	Glaciers only
Dark Glacier	3	Glaciers only
Dome Glacier	2	Glaciers only
Douglas Glacier	4	Glaciers and perennial snowfields
Dusty Glacier	2	Glaciers and perennial snowfields
East Nooksack Glacier	5	Glaciers only
Entiat Glacier	4	Glaciers and perennial snowfields
Forbidden Glacier	2	Glaciers only
Fremont Glacier	2	Glaciers only
Goode Glacier	2	Glaciers only

Hadley Glacier	5	Glaciers only
Hanging Glacier	2	Glaciers only
Hinman Glacier	4	Glaciers only
Honeycomb Glacier	3	Glaciers and perennial snowfields
Inspiration Glacier	3	Glaciers and perennial snowfields
Isella Glacier	2	Glaciers and perennial snowfields
Jerry Glacier	2	Glaciers only
Kimtah Glacier	3	Glaciers only
LeConte Glacier	7	Glaciers and perennial snowfields
Lyall Glacier	2	Perennial snowfields only
Mazama Glacier	3	Glaciers and perennial snowfields
McAllister Glacier	2	Glaciers only
Middle Cascade Glacier	2	Glaciers only
Neve Glacier	3	Glaciers only
No Name Glacier	5	Glaciers and perennial snowfields
Nohokomeen Glacier	2	Glaciers only
North Klawatti Glacier	2	Glaciers and perennial snowfields
Pilz Glacier	3	Glaciers and perennial snowfields
Price Glacier	4	Glaciers only
Ptarmigan Glacier	2	Glaciers and perennial snowfields
Queest-alb Glacier (not official)	3	Glaciers and perennial snowfields
Rainbow Glacier	3	Glaciers and perennial snowfields
Redoubt Glacier	2	Glaciers only
Richardson Glacier	2	Glaciers only
S Glacier	3	Glaciers only
Sandalee Glacier	4	Glaciers only
Scimitar Glacier	3	Glaciers only
Sholes Glacier	4	Glaciers only
Sitkum Glacier	4	Glaciers and perennial snowfields
Snow Creek Glacier	2	Perennial snowfields only
South Cascade Glacier	2	Glaciers only
Spider Glacier	2	Glaciers only
Suiattle Glacier	2	Glaciers only
Sulphide Glacier	2	Glaciers only
Thunder Glacier	3	Glaciers only
Thunder Glacier	2	Glaciers only
White Chuck Glacier	5	Glaciers and perennial snowfields
White Salmon Glacier	2	Glaciers only
Wyeth Glacier	3	Glaciers and perennial snowfields

Cascade Range-Southern

Adams Glacier	4	Glaciers and perennial snowfields
Avalanche Glacier	2	Glaciers only
Conrad Glacier	3	Glaciers and perennial snowfields
Cowlitz Glacier	2	Glaciers and perennial snowfields
Crescent Glacier	2	Glaciers and perennial snowfields
Flett Glacier	6	Glaciers and perennial snowfields
Fryingpan Glacier	5	Glaciers and perennial snowfields
Gotchen Glacier	2	Glaciers and perennial snowfields
Kautz Glacier	2	Glaciers and perennial snowfields

Klickitat Glacier	2	Glaciers only
Lava Glacier	3	Glaciers and perennial snowfields
McCall Glacier	6	Glaciers and perennial snowfields
Meade Glacier	5	Perennial snowfields only
North Mowich Glacier	2	Glaciers and perennial snowfields
Ohanapecosh Glacier	6	Glaciers and perennial snowfields
Paradise Glacier	3	Glaciers and perennial snowfields
Pinnacle Glacier	3	Glaciers and perennial snowfields
Puyallup Glacier	2	Glaciers and perennial snowfields
Pyramid Glacier	4	Glaciers and perennial snowfields
Russell Glacier	2	Glaciers only
Sarvant Glaciers	4	Glaciers and perennial snowfields
South Mowich Glacier	2	Glaciers only
South Tahoma Glacier	2	Glaciers and perennial snowfields
Success Glacier	2	Glaciers and perennial snowfields
Van Trump Glacier	10	Glaciers and perennial snowfields
White Salmon Glacier	2	Glaciers only
Whitman Glacier	5	Glaciers and perennial snowfields
Wilson Glacier	3	Glaciers and perennial snowfields

Olympic Mountains

Blue Glacier	2	Glaciers only
Cameron Glaciers	4	Glaciers and perennial snowfields
Carrie Glacier	2	Glaciers only
Eel Glacier	2	Glaciers only
White Glacier	2	Glaciers only

Wyoming
Teton Range

Middle Teton Glacier	2	Glaciers and perennial snowfields
Triple Glaciers	3	Glaciers only

Wind River Range

Bull Lake Glacier	3	Glaciers and perennial snowfields
Dinwoody Glacier	2	Glaciers only
Dinwoody Glaciers	3	Glaciers and perennial snowfields
Grasshopper Glacier	3	Glaciers only
Harrower Glacier	2	Perennial snowfields only
Helen Glacier	3	Glaciers only
Lower Fremont Glacier	4	Glaciers and perennial snowfields
Mammoth Glacier	2	Glaciers and perennial snowfields
Minor Glacier	2	Glaciers and perennial snowfields
Sacagawea Glacier	4	Glaciers and perennial snowfields
Sourdough Glacier	2	Glaciers and perennial snowfields
Stroud Glacier	3	Glaciers and perennial snowfields
Twins Glacier	2	Glaciers and perennial snowfields
Upper Fremont Glacier	2	Glaciers and perennial snowfields

368

369

370 **A3 Labelling errors in the U.S. Geographic Names Information System**

371 **Table A3**. List of officially named glaciers where we identified an issue with the glacier name
372 on the 1:24000 U.S. Geological Survey topographical maps (Fountain et al., 2017). Names come
373 from the Geographic Names Information System (https://www.usgs.gov/tools/geographic-
374 names-information-system-gnis). The 'Issue' column lists the type of issue identified. 'Not
375 labeled' indicates the feature was present but not labeled, 'Misidentified' indicates the wrong
376 feature was labeled, and 'Label unclear' means the location of the label is not clearly associated
377 with a specific glacier.

State/Region/Glacier Name	Issue
Colorado	
Front Range	
Arikaree Glacier	Not labeled
Navajo Glacier	Not labeled
Oregon	
Cascade Range	
Carver Glacier	Misidentified
Milk Creek Glacier	Not labeled
Washington	
Cascade Range-Northern	
S Glacier	Label unclear
Snow Creek Glacier	Label unclear
South Glacier	Not labeled
Cascade Range-Southern	
No Name Glacier	Not labeled
Stevens Glacier	Not labeled
Wyoming	
Wind River Range	
Dinwoody Glaciers	Label unclear
Fremont Glaciers	Label unclear

378

379
380 **A4 Notes on imagery and interpretation challenges by State.**
381
382 This appendix, organized by US State, then by mountain range, summarizes the specific
383 imagery used, challenges encountered in feature identification and outline digitization. The
384 Selkowitz and Forster (2016) inventory is referred to as the SFI and the National Land Cover
385 Database inventory (Dewitz, 2019) is referred to as the NLCD.
386
387 **A4.1 California**
388
389 Imagery and DEMs used are listed in Tables A4, A5, A6.
390
391 **Cascade Range**
392
393   **Mount Shasta**
394

395　The 2020 black and white Maxar imagery was most useful because of the minimal
396　seasonal snow cover. The 2018 NAIP imagery was helpful in situations where the 2020
397　imagery was obscured by shadow, distortion, or misaligned, and when color was needed
398　to improve interpretation. The 2010 lidar DEM (Robinson, 2014; Table A4) was used to
399　create a multidirectional hillshade to improve perspective and interpretation (Figure A1).
400　The rock debris on the termini of most glaciers and rock debris on some of the upper
401　parts of the glaciers were challenging to interpret. It was hard to determine whether ice
402　was present under the debris and whether that ice is part of the active glacier. Spatial
403　patterns of debris, debris contrasts, and melt streams flowing from the debris were used to
404　estimate the glacier boundaries.
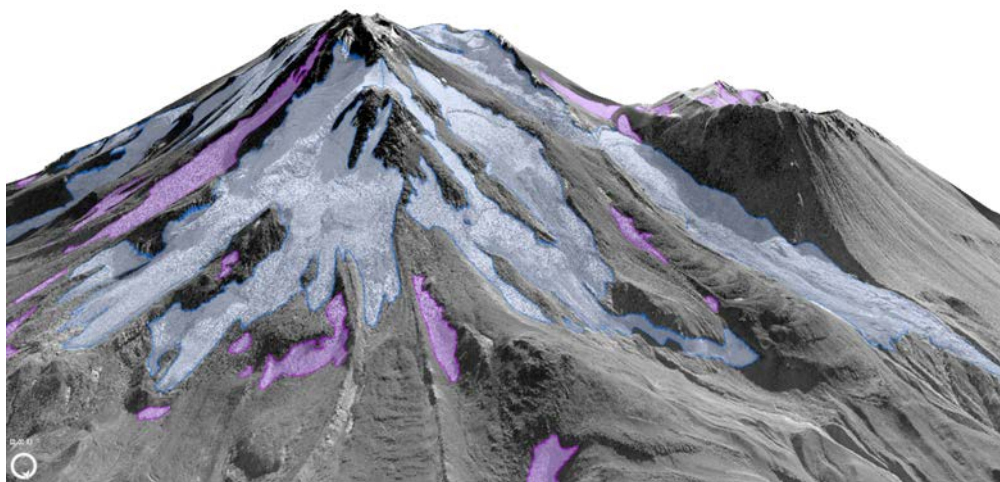
405

406　**Figure A1.** Mt. Shasta glaciers in bluish white, perennial snowfields/ice patches in lavender
407　draped over a 3D rendering created from 2010 lidar (Robinson, 2014).

408

409

Sierra Nevada

411　The 2014 NAIP imagery was the best imagery due to low snow cover. In some cases,
412　features were difficult to outline because of shadow or image quality. In these cases,
413　2013/2012 Google Earth imagery were used. Some glaciers were reclassified as rock
414　glaciers by Trcka (2020). These were re-examined and where we agreed they were
415　removed from the initial glacier inventory. Defining whether the feature was a glacier or
416　rock glacier was often difficult, see Colorado section for more discussion.

417

Trinity Alps

419　The 2018 imagery was the best for the least snow cover. Justin Garwood (Garwood et al.,
420　2020) provided outlines for two glaciers, Grizzly and Salmon. The area of the most recent
421　outline of the Salmon Glacier was < 0.01 km^2 and was not included in this inventory. By
422　2018 all of the other features mapped by the USGS (Fountain et al., 2017) were less than
423　0.01 km^2 or had disappeared. An additional feature was added based on the 2016 NLCD
424　(Jin et al., 2019).

425

426

427 **Table A4.** List of NAIP imagery used for outlining glaciers and perennial snowfields in
428 California. 'Date' is the start and end date for flights covering the glaciated portions of the NAIP
429 image. In some cases, flights were completed in a single day.
430

Region/Year/Filename	County	Date (Year-M-D)
Cascade Range		
2014		
ortho_1-1_1n_s_ca089_2014_1.sid	Shasta	2014-07-13
ortho_1-1_1n_s_ca093_2014_1.sid	Siskiyou	2014-06-23 to 2014-07-18
2018		
ortho_1-1_hn_s_ca093_2018_1.sid	Siskiyou	2018-07-21 to 2018-09-25
Sierra Nevada		
2014		
ortho_1-1_1n_s_ca019_2014_1.sid	Fresno	2014-07-23 to 2014-08-23
ortho_1-1_1n_s_ca027_2014_1.sid	Inyo	2014-07-23 to 2014-08-23
ortho_1-1_1n_s_ca039_2014_2.sid	Madera	2014-07-18 to 2014-08-15
ortho_1-1_1n_s_ca051_2014_1.sid	Mono	2014-07-17 to 2014-08-15
ortho_1-1_1n_s_ca107_2014_1.sid	Tulare	2014-08-23 to 2014-08-23
Trinity Alps		
2018		
ortho_1-1_hn_s_ca093_2018_1.sid	Siskiyou	2018-07-21 to 2018-09-25

431
432
433 **Table A5**. List of dates of the Maxar imagery used for outlining glaciers and perennial
434 snowfields in California.

Region/ Date (Year-M-D)
Cascade Range
2020-10-05

435
436
437 **Table A6**. List of U.S. Geological Survey digital elevation models used for outlining glaciers
438 and perennial snowfields in California.

Filename	Date	Citation	URL
ds852_lidar	2010	Robinson (2014)	https://pubs.er.usgs.gov/publication/ds852

439
440 **A4.2 Colorado**
441
442 The 2015 NAIP was generally free of seasonal snow. Where it persisted at the terminus of a few
443 glaciers, images for the same year in Google Earth aided perimeter interpretation. Imagery used

are listed in Table A7.

Elk Mountains

No features were mapped in the Elk Mountains by the USGS (Fountain et al., 2017). One glacier and four perennial snowfields were added from the SFI.

Front Range

The most recent inventory for the Front Range was Hoffman et al. (2007), which used aerial photographs to map the 2001 extent of glaciers. Many features in the Front Range are difficult to classify. The issue is the difference between a glacier or perennial snowfield and a rock glacier. Those that are part of the rock glacier are deleted from the glacier inventory. Those that seem to be separate from rock glaciers are retained. This is a judgement call. From a hydrological point of view, if a snow-ice patch that is part of a rock glacier was counted separately from a rock glacier, it is double counting a water feature.

Table A7. List of NAIP imagery used for outlining glaciers and perennial snowfields in Colorado. 'Date' is the start and end date for flights covering the glaciated portions of the NAIP image. In some cases, flights were completed in a single day.

Region/Year/Filename	County	Date (Year-M-D)
Elk Mountains		
2015		
ortho_1-1_1n_s_co051_2015_1.sid	Gunnison	2015-09-10 to 2015-09-11
Front Range		
2015		
ortho_1-1_1n_s_co013_2015_1.sid	Boulder	2015-08-25 to 2015-09-20
ortho_1-1_1n_s_co049_2015_1.sid	Grand	2015-08-25 to 2015-09-20
ortho_1-1_1n_s_co057_2015_1.sid	Jackson	2015-09-09
ortho_1-1_1n_s_co069_2015_1.sid	Larimer	2015-08-25 to 2015-09-09
Gore Range		
2015		
ortho_1-1_1n_s_co037_2015_1.sid	Eagle	2015-09-10
Medicine Bow Mountains		
2015		
ortho_1-1_1n_s_co057_2015_1.sid	Jackson	2015-09-09
Park Range		
2015		
ortho_1-1_1n_s_co057_2015_1.sid	Jackson	2015-09-09
San Miguel Mountains		
2015		
ortho_1-1_1n_s_co033_2015_1.sid	Dolores	2015-09-11
ortho_1-1_1n_s_co091_2015_1.sid	Ouray	2015-09-11
ortho_1-1_1n_s_co111_2015_1.sid	San Juan	2015-09-12

Sawatch Range
  2015

Region/Year/Filename	County	Date (Year-M-D)
ortho_1-1_1n_s_co037_2015_1.sid	Eagle	2015-09-10
ortho_1-1_1n_s_co097_2015_1.sid	Pitkin	2015-09-10 to 2015-09-11

465

466 **A4.3 Idaho**

467

468 The imagery quality was generally snow free. Of the glacier mapped by the USGS (Fountain et
469 al., 2017) only two remain and are classified as perennial snowfields. The Borah Glacier was
470 officially named in 2021 (U.S. Board of Geographic Names), but is < 0.01 km^2, and is not
471 included in the inventory. Table A8 lists the imagery used.

472

473

474 **Table A8.** List of NAIP imagery used for outlining glaciers and perennial snowfields in Idaho.
475 'Date' is the start and end date for flights covering the glaciated portions of the NAIP image. In
476 some cases, flights were completed in a single day.

477

Region/Year/Filename	County	Date (Year-M-D)
Sawtooth Range		
2013		
ortho_1-1_hn_s_id015_2013_1.sid	Boise	2013-09-07
2015		
ortho_1-1_1n_s_id013_2015_1.sid	Blaine	2015-07-30
ortho_1-1_1n_s_id015_2015_1.sid	Boise	2015-09-08 to 2015-09-09
2019		
ortho_1-1_hn_s_id037_2019_1.sid	Custer	2019-07-25 to 2019-08-26

478
479

480 **A4.4 Montana**

481

482 Inage quality varied between mountain ranges due to differences in snow cover. Tables A9 and
483 A10 list the imagery used.

484

    Beartooth-Absaroka Range
486   The 2015 NAIP imagery was the best overall imagery due to the least snow, but Google
487   Earth was occasionally used as well. Google Earth had imagery dated to 9/11/2015; often
488   with less seasonal snow than the NAIP imagery. To counter any mismatch in projection,
489   outlines digitized in Google Earth were imported to ArcGIS and projected to match the
490   NAIP projection.
491   **Bitterroot Range**
492   No features were mapped in the Bitterroot Range by the USGS (Fountain et al., (2017).
493   One glacier and three perennial snowfields were added based on the NLCD.

494

495   **Cabinet Range**

496   The USGS mapped four features ≥ 0.01 km^2 (Fountain et al., 2017). Inspection of the
497   2015 only one was ≥ 0.01 km^2. Seven glaciers and perennial snowfields were added; five
498   were identified in our initial inventory, the other two were identified by the SFI and
499   NLCD, respectively. All were less than 0.05 km^2.
500
501 **Crazy Mountains**
502   The 2013 NAIP imagery was the best imagery available and included limited seasonal
503   snow. The 2019 Maxar imagery had too much seasonal snow.
504
505 **Lewis Range (Glacier National Park)**
506   The most recent published glacier inventory is a 2015 USGS inventory (Fagre et al.,
507   2017). They outlined the main-body of named-glaciers using 2015 Maxar imagery. We
508   digitized the outlines of all glaciers and perennial snowfields using 2015 Maxar imagery
509   where available. Elsewhere, 2015 and 2013 NAIP imagery were used; both years had lots
510   of seasonal snow cover. Two major glaciers, Blackfoot (Figure A2) and Harrison (Figure
511   A3) glaciers, separated into pieces as it retreated since it was originally mapped by the
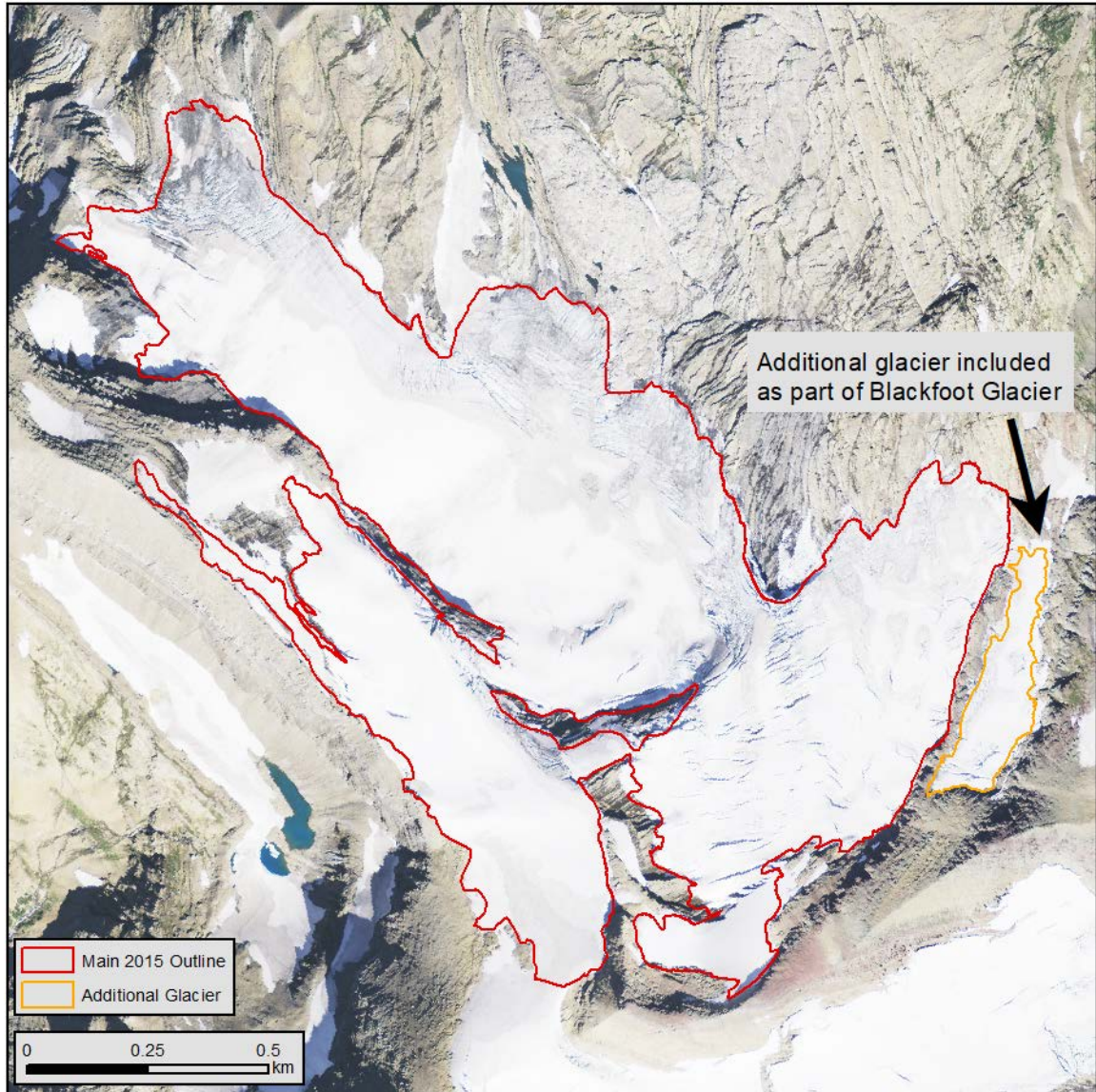512   USGS (Fountain et al., 2007).
513
514 **Madison Range**
515   The 2013 NAIP imagery was the only imagery used due to extensive snow in the other
516   years. No glaciers or perennial snowfields were found. Of the two features ≥ 0.01 km^2
517   mapped by the USGS (Fountain et al., 2017), the 2013 imagery showed that one feature
518   is a rock glacier and the other was less than 0.01 km^2.
519
520 **Mission-Swan-Flathead Ranges**
521   Based on the least snow cover, the 2013 NAIP was better in the Mission and Flathead
522   Ranges, and the 2015 NAIP was better in the Swan Range. No glaciers or perennial
523   snowfields remain in the Flathead Range.
524

Additional glacier included as part of Blackfoot Glacier

Main 2015 Outline
Additional Glacier

0   0.25   0.5
km

525

Figure A2. The updated (2015) outlines for the Blackfoot Glacier including the main glacier body (red) and the additional smaller glacier (orange). Base image from the NAIP taken in 2013.

528
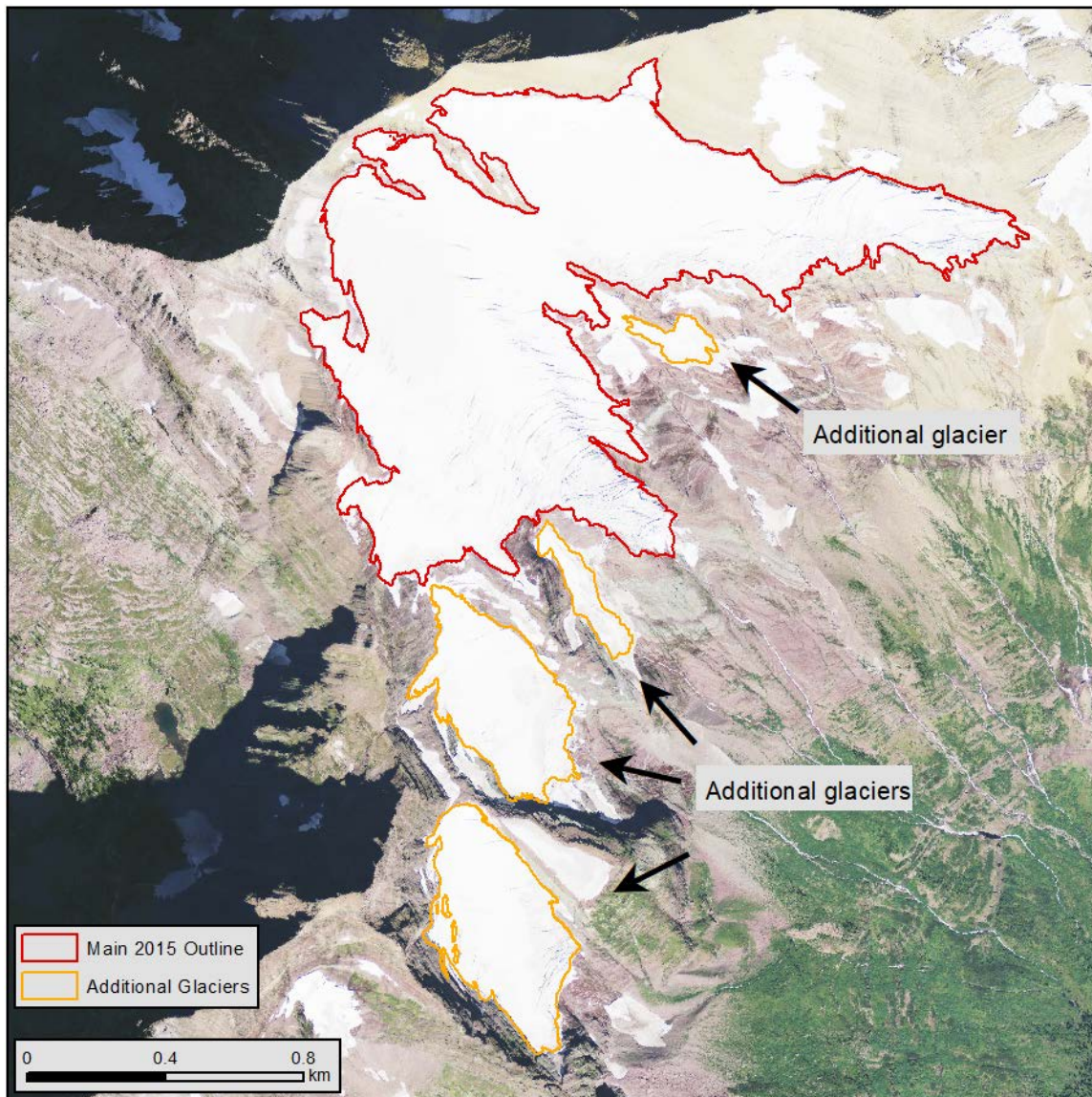
Figure A3. The updated (2015) outlines for Harrison Glacier including the main glacier body (red) and the additional smaller glaciers (orange). Base image from the NAIP taken in 2013.

Table A9. List of NAIP imagery used for outlining glaciers and perennial snowfields in Montana. 'Date' is the start and end date for flights covering the glaciated portions of the NAIP image. In some cases, flights were completed in a single day.

Region/Year/Filename	County	Date (Year-M-D)
Beartooth Mountains-Absaroka Range		
2013		
ortho_1-1_1n_s_mt067_2013_1.sid	Park	2013-08-05 to 2013-09-11

2015

ortho_1-1_1n_s_mt009_2015_1.sid	Carbon	2015-08-10 to 2015-09-07
ortho_1-1_1n_s_mt067_2015_1.sid	Park	2015-08-19 to 2015-09-11
ortho_1-1_1n_s_mt095_2015_1.sid	Stillwater	2015-08-10 to 2015-09-07

Bitterroot Range

2013

ortho_1-1_1n_s_mt001_2013_1.sid	Beaverhead	2013-08-04

2015

ortho_1-1_1n_s_mt081_2015_2.sid	Ravalli	2015-10-06 to 2015-11-07

Cabinet Mountains

2015

ortho_1-1_1n_s_mt053_2015_2.sid	Lincoln	2015-09-11 to 2016-08-15

Crazy Mountains

2013

ortho_1-1_1n_s_mt067_2013_1.sid	Park	2013-08-05 to 2013-09-11
ortho_1-1_1n_s_mt097_2013_1.sid	Sweet Grass	2013-08-31 to 2013-09-10

2015

ortho_1-1_1n_s_mt067_2015_1.sid	Park	2015-08-19 to 2015-09-11

Lewis Range

2013

ortho_1-1_1n_s_mt029_2013_1.sid	Flathead	2013-08-21 to 2013-09-01
ortho_1-1_1n_s_mt035_2013_1.sid	Glacier	2013-08-21 to 2013-09-01

2015

ortho_1-1_1n_s_mt029_2015_2.sid	Flathead	2015-09-30 to 2016-10-21
ortho_1-1_1n_s_mt035_2015_2.sid	Glacier	2015-10-14 to 2016-08-21

Mission Range-Swan-Flathead Ranges

2013

ortho_1-1_1n_s_mt029_2013_1.sid	Flathead	2013-08-21 to 2013-09-01
ortho_1-1_1n_s_mt063_2013_1.sid	Missoula	2013-09-01

2015

ortho_1-1_1n_s_mt047_2015_2.sid	Lake	2015-09-12 to 2016-08-15
ortho_1-1_1n_s_mt063_2015_2.sid	Missoula	2015-09-12 to 2016-08-16

537
538
539 **Table A10.** List of dates of the Maxar imagery used for outlining glaciers and perennial
540 snowfields in Montana.
541

Region/ Date (Year-M-D)

   Lewis Range
     2015-08-22
     2015-09-01
     2015-09-12
     2015-09-25
     2019-08-20

542   **A4.5 Oregon**

543

544   Tables A11, A12, and A13 list the imagery and DEM used.

545

546   **Cascade Range**

547

548   Seasonal snow cover was commonly present when this range was imaged by any of the
549   sensors making it difficult to find suitable imagery.

550

551   **Mount Hood**
552   The most recent glacier outlines for Mt. Hood were based on 2015 and 2016 Maxar color
553   imagery with interpretation aid using Google Earth. Due to seasonal snow some
554   professional judgement was required in places.

555

556   **Mount Jefferson**
557   The 2018 NAIP had extensive seasonal snow and was generally only useful near the
558   terminus of some glaciers. Used 2018 Maxar imagery that showed little seasonal snow,
559   but a little cloudy that masked a bit of Whitewater Glacier. Also used Google Earth to
560   help interpret some of the features.

561

562   **Three Sisters**
563   Maxar 2018 imagery was used, but the image was stretching along the feature's headwall
564   and for that segment of the outline 2018 NAIP imagery was used. Two versions of the
565   Maxar imagery for the same day are available, one color, one black and white. Color was
566   georectified but suffered stretching along some headwalls. A light early season snowfall
567   occurred before the Maxar image and the snow accumulated in some places just enough
568   to obscure the surface. So, the glacier or snow patch outline was the minimum of the two
569   images with occasional interpolation across the snowy surface to the nearest glacier edge.

570

571   **Mount Thielsen**
572   The Lathrop Glacier was named in 1981. At the time of the USGS mapping and now it is
573   <0.01 km^2, and not counted as part of the inventory. Furthermore, Lathrop Glacier has
574   been known to disappear in some years and therefore fails the definition of a glacier.

575

576   **Wallowa Mountains**
577   No NAIP imagery was useful and Maxar did not image this region. We used the
578   8/30/2013 image from Google Earth, which was excellent with little snow. Features were
579   digitized in Google Earth and then imported into ArcGIS. Because we used NAIP as the
580   base imagery, we revised the outline from the projection in WGS84 (Google Earth) to
581   NAD83 UTM Zone 11 (NAIP).

582

583

584   **Table A11.** List of NAIP imagery used for outlining glaciers and perennial snowfields in
585   Oregon. 'Date' is the start and end date for flights covering the glaciated portions of the NAIP

586   image. In some cases, flights were completed in a single day.
587

Region/Year/Filename	County	Date (Year-M-D)
Cascade Range		
2014		
ortho_1-1_1n_s_or017_2014_1.sid	Deschutes	2014-09-01
ortho_1-1_1n_s_or027_2014_1.sid	Hood River	2014-08-27 to 2014-09-05
ortho_1-1_1n_s_or039_2014_1.sid	Lane	2014-09-01
2016		
ortho_1-1_1n_s_or027_2016_1.sid	Hood River	2016-08-04
2017/2018		
ortho1-1_hn_s_or017_2017_2018_1.sid	Deschutes	2018-07-28
Wallowa Mountains		
2014		
ortho_1-1_1n_s_or063_2014_1.sid	Wallowa	2014-10-05

588
589
590   **Table A12**. List of dates of the Maxar imagery used for outlining glaciers and perennial
591   snowfields in Oregon.
592

Region/ Date (Year-M-D)
Cascade Range
2015-08-20
2015-09-11
2015-10-05
2016-09-10
2018-09-17
2020-09-20

593
594
595   **Table A13.** List of Oregon Department of Geology and Mineral Industries digital elevation
596   models used for outlining glaciers and perennial snowfields in Oregon.
597

Filename	Date	URL
2011_OLC_Deschutes	2011	gis.dogami.oregon.gov/maps/lidarviewer/

598
599
600   **A4.6 Washington**
601
602   The 2015 NAIP imagery was typically excellent with little snow cover, whereas the 2017 NAIP
603   had more snow and the 2019 imagery had lots of snow. For most outlines, 2015 NAIP imagery
604   was used. In some places, the 2017 NAIP imagery had less snow and was used instead. Maxar
605   imagery was of limited use and often wasn't better than the 2015 or 2017 NAIP. Tables A14,
606   A15, A16, list the imagery and DEMs used.
607

Cascade –Northern

The glaciers and perennial snowfields were previously inventoried by (Dick, 2013).

Mount Baker

The 2015 NAIP imagery was the best and had little seasonal snow. Google Earth 2009 and 2019 imagery were used to help interpretation. A multidirectional hillshade and 3-meter contour lines derived from a lidar DEM (Bard, 2017a); were used to help define flow divides between glaciers, debris covered-ice, and buried ice. There are notable differences between the NAIP imagery and DEM data, particularly in steep terrain, areas of dark shadow, and debris-covered areas. The DEM helped correct these positional errors and the benefit of supplying more information on surface texture.

Several buried-ice features were identified. The ice appeared to have decoupled from the active glacier. In a few cases, debris-covered ice is included in the glacier outline because the ice appears to be directly connected to the glacier, and there was evidence of movement.

Dragontail Peak

The USGS Geographic Names Information Service (GNIS) locates Snow Creek Glacier at a point on the edge of the southeast glacier (Fountain et al., 2007). In the 2015 imagery, the point is on bedrock, making it unclear which glacier the GNIS is naming. The USGS identifies both glaciers as Snow Creek Glacier. We labeled both glaciers as the Snow Creek Glacier.

Glacier Peak

For the Glacier Peak region, a multidirectional hillshade and 3-m contour lines derived from a 2015 lidar DEM (Bard, 2017b) were used as a guide to define flow divides.

Hurry-up Peak

The point location of the South Glacier provided by the GNIS is over bedrock. We assume the point refers to the glacier located ~150 m to the north of the point.

Cascade –Southern

Goat Rocks

Imagery from 2015 was best, but had more snow than desired. Too much snow was present in 2017 but some ice was exposed. The 2019 imagery was too snowy for glacier digitization.

The outlines are almost entirely based on 2015 imagery, and a few on 2017, where needed. Used 2009 NAIP imagery to help define the headwalls at the Conrad, McCall, and Packwood glaciers. Heard (2000) previously mapped the glacier perimeters. The maximum extent of the seasonal snow covering the terminal regions was not digitized. Typically digitized at scales of 1:600 to 1:800. Note that narrow arms of the snowfields were not typically digitized knowing that they would probably disappear a few days to a

653   week from the time of imagery.
654
655   **Mount Adams**
656   No suitable NAIP imagery was found, instead 2019 Maxar imagery was used. In addition
657   to the Maxar imagery, a multidirectional hillshade and 3-m contour lines derived from a
658   2016 lidar DEM (Bard 2019) were used as a guide when delingating flow divides.
659   Occasionally, 2009 Google Earth imagery was also useful. Extensive snow covered the
660   mountain when the 2016 lidar was flown masking some of the glacier termini. However,
661   the DEM was helpful in correcting the imagery where poorly aligned with the terrain.
662
663   Multiple buried-ice features were identified near the terminus of several glaciers where
664   ice appeared to have decoupled from the main active glacier. Large areas below the
665   glaciers (Mazama, Adams, and Pinnacle) likely have debris-covered ice. We focused on
666   the features which were likely to contain ice based on meltwater streams exiting near the
667   features and hummocky terrain which appeared to indicate melt. Ground-based images
668   from taken between 2014 to 2018 helped decision-making. The images were particularly
669   helpful in identifying a debris-covered ice cliff at Adams Glacier.
670
671   **Mount Rainier**
672   In general, the 2019 NAIP and the Maxar (2018-09-25) were used for the outlines.
673   Although the GNIS includes the Nisqually Icefall as a separate feature, we included the
674   icefall as part of the Nisqually Glacier (Figure A4).
675
676   **Mount St. Helens**
677   We used a GIS layer of geological mapping units that included snow and ice from the
678   USGS (David Sherrod, USGS written communication, 2021) to help guide our search.
679   The Crater Glacier (INV_ID E562842N5115499) was heavily debris covered, and
680   obscured by shadow in some areas.
681
682 **Olympic Mountains**
683
684   A 2015 inventory of the region was compiled because more recent imagery (NAIP and
685   Maxar) were not useful due to seasonal snow. Our updated inventory differs from that
686   published in Fountain et al. (2017) in two ways. First, they outlined and grouped the
687   glaciers and perennial snowfields according to watershed rather than individual glacier.
688   Their goal was to estimate glacier change relative to a previous study by Spicer (1986)
689   and had to follow Spicer's approach. Second, all outlines were rechecked and compared
690   to SFI and the NLCD resulting in minor changes.
691
692
693

694
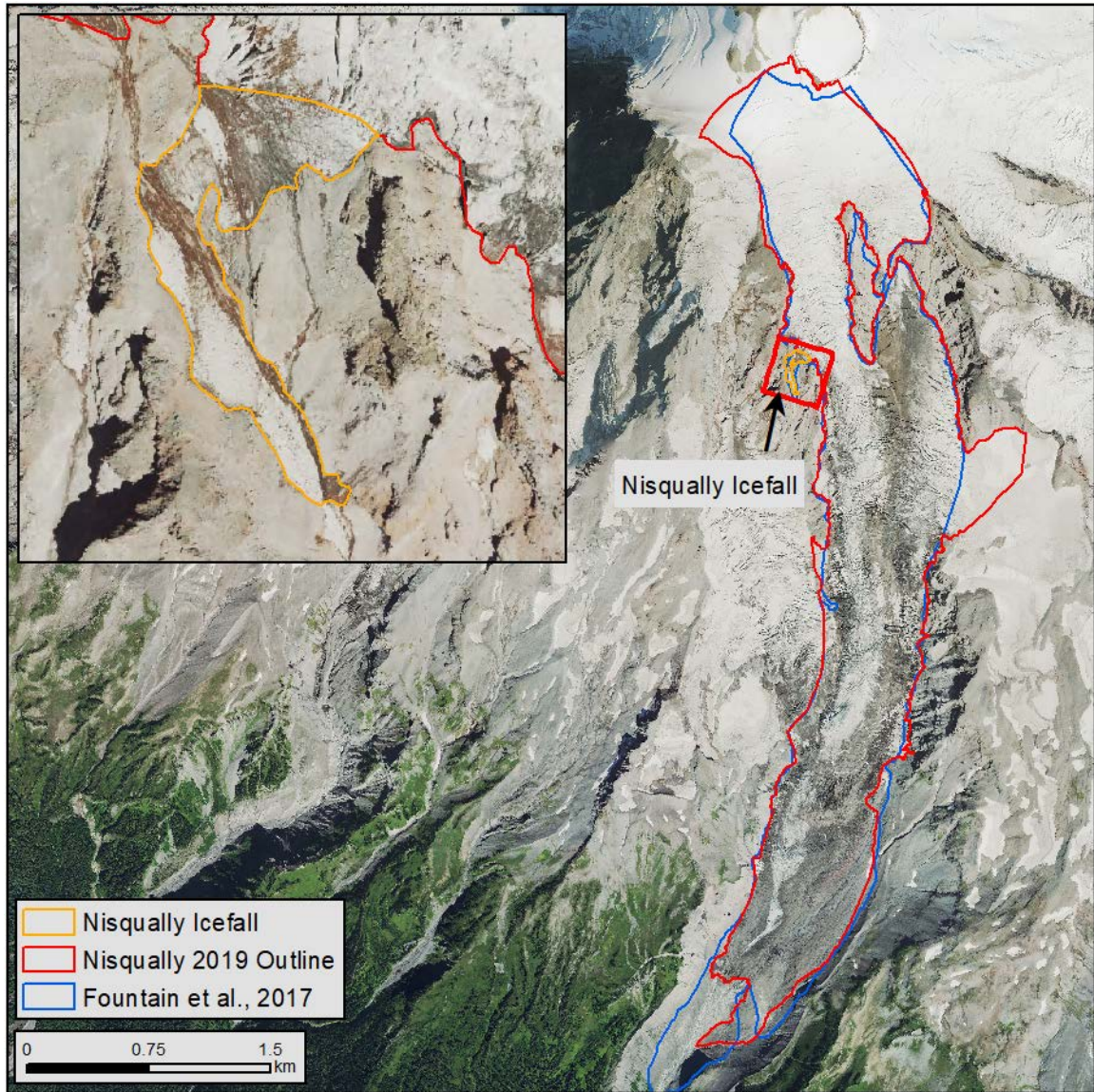
Figure A4. Image of the Nisqually Glacier and Icefall. The orange and red outlines are from the updated inventory and the blue outline is from the USGS mapping (Fountain et al., 2007) database. The base image is from the NAIP taken in 2019.

Table A14. List of NAIP imagery used for outlining glaciers and perennial snowfields in Washington. 'Date' is the start and end date for flights covering the glaciated portions of the NAIP image. In some cases, flights were completed in a single day. For 2006 the inspection date was used, since the start and end dates were not provided.

Region/Year/Filename	County	Date (Year-M-D)
Cascade –Northern		

2006
ortho_1-1_1n_s_wa007_2006_3.sid   Chelan   2006-07-01
2015
  ortho_1-1_1n_s_wa007_2015_1.sid   Chelan   2015-07-06 to 2015-09-23
  ortho_1-1_1n_s_wa033_2015_1.sid   King   2015-07-06 to 2015-09-27
  ortho_1-1_1n_s_wa037_2015_1.sid   Kittitas   2015-07-06 to 2015-09-23
  ortho_1-1_1n_s_wa047_2015_1.sid   Okanogan   2015-09-09 to 2015-09-11
  ortho_1-1_1n_s_wa057_2015_1.sid   Skagit   2015-07-06 to 2015-09-29
  ortho_1-1_1n_s_wa061_2015_1.sid   Snohomish   2015-07-06 to 2015-09-29
  ortho_1-1_1n_s_wa073_2015_1.sid   Whatcom   2015-09-10 to 2015-09-26
2017
  ortho_1-1_1n_s_wa007_2017_1.sid   Chelan   2017-10-03 to 2017-10-24
  ortho_1-1_1n_s_wa057_2017_1.sid   Skagit   2017-09-27 to 2017-10-05
  ortho_1-1_1n_s_wa073_2017_1.sid   Whatcom   2017-09-27 to 2017-10-05

Cascade –Southern
2015
  ortho_1-1_1n_s_wa041_2015_1.sid   Lewis   2015-07-15 to 2015-07-29
  ortho_1-1_1n_s_wa053_2015_1.sid   Pierce   2015-07-29
  ortho_1-1_1n_s_wa059_2015_1.sid   Skamania   2015-07-15 to 2015-09-12
  ortho_1-1_1n_s_wa077_2015_1.sid   Yakima   2015-07-15 to 2015-07-29
2019
  ortho_1-1_hn_s_wa053_2019_1.sid   Pierce   2019-08-26
  ortho_1-1_hn_s_wa059_2019_1.sid   Skamania   2019-08-06 to 2019-08-26

Olympic Mountains
2015
  ortho_1-1_1n_s_wa009_2015_1.sid   Clallam   2015-07-28 to 2015-09-12
  ortho_1-1_1n_s_wa031_2015_1.sid   Jefferson   2015-07-28 to 2015-09-12
  ortho_1-1_1n_s_wa045_2015_1.sid   Mason   2015-07-28 to 2015-08-19

Table A15. List of dates of the Maxar imagery used for outlining glaciers and perennial snowfields in Washington.

Region/ Date (Year-M-D)
Cascade Range-Northern
2018-09-25
Cascade Range-Southern
2018-09-25
2019-08-31
Olympic Mountains
2015-08-17
2019-09-30

Table A16. List of U.S. Geological Survey digital elevation models used for outlining glaciers

713 and perennial snowfields in Washington. To access the data both the URL and specific identifier
714 are required.

Region	Date	Citation	URL www.sciencebase.gov/catalog/item/
Mt. Adams	2016	Bard (2019)	5bc623b9e4b0fc368ebbe99a
Mt. Baker	2015	Bard (2017a)	58518b0ee4b0f99207c4f12c
Glacier Peak	2014-15	Bard (2017b)	57bf299ee4b0f2f0ceb7534e

715
716
717 **A7 Wyoming**
718
719 **Wind River Range**
720
721 Tables A17 and A18 list the imagery used. The 2015 NAIP imagery had little snow in
722 contrast to 2019 imagery. Shadows are common in the 2015 imagery and can be very
723 dark. Occasionally the 2019 imagery was used to define the glacier-bedrock headwall
724 boundary. The 2019 Maxar imagery was essentially identical to the NAIP and because its
725 black and white not as useful. Imagery from 2017 and 2018 were a bit too snowy around
726 the glacier margin to be useful. The 2018-09-06 Maxar imagery covered the entire range,
727 with some clouds.

728 In the southern Wind River Range, a new snow dusting was often present, occasionally
729 making it difficult to outline snowfields and a few glaciers. Distinguishing seasonal snow
730 from perennial snow was a judgement call. If the snow was slightly discolored similar to
731 underlying rock/soil looking like the color was coming from underneath it was identified
732 as seasonal snow. Also, if many snow-free patches (a few square meters) pockmarked the
733 snow or if many rocks protruded through the snow, it was considered seasonal. A
734 perennial patch of snow appeared smooth and white, hiding underlying surface. Thin
735 snow cover on glacier ice appeared greyish in color and appeared smoother than the
736 surrounding ice-free landscape.

737 At Lower Fremont Glacier, a number of sizable ice patches appear down valley as if a
738 deposit of buried ice is present. However, there is no obvious connection to the glacier
739 itself.

740 The GNIS identified a single glacier as the Sacagawea Glacier, and two separate Fremont
741 Glaciers (Figure A5). By 2017 the single glacier had split into four glaciers. We chose to
742 label the largest glacier and the glacier to the southeast the Sacagawea Glacier. The other
743 two glaciers were labeled the Fremont Glaciers.

744
745

746

747
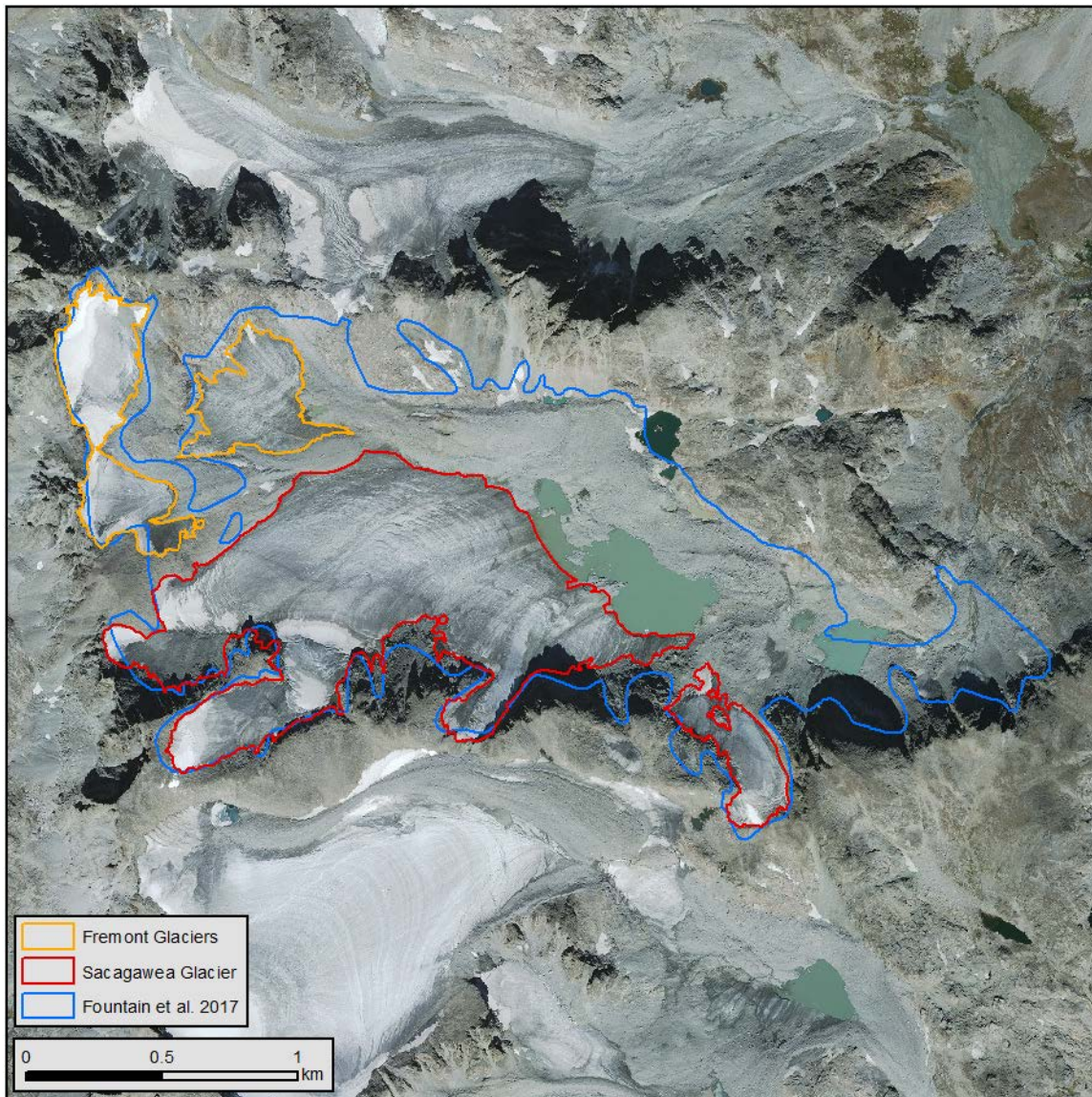
Figure A5. Image of Fremont Glaciers and Sacagawea Glacier showing the Sacagawea outline
from the Fountain et al. (2017) database (blue), our updated Fremont Glaciers outlines (orange),
and updated Sacagawea outlines (red). The base image is from the NAIP, taken in 2015.

Table A17. List of NAIP imagery used for outlining glaciers and perennial snowfields in
Wyoming. 'Date' is the start and end date for flights covering the glaciated portions of the NAIP
image. In some cases, flights were completed in a single day. For 2006 the inspection date was
used, since the start and end dates were not provided.

Region/Year/Filename	County	Date (Year-M-D)
Absaroka Range		

2006
  ortho_1-2_1n_s_wy029_2006_1.sid Park   2006-09-02
2015
  ortho_1-1_hn_s_wy013_2015_2.sid Fremont 2015-09-09 to 2015-10-13
  ortho_1-1_hn_s_wy029_2015_2.sid Park   2015-09-22 to 2015-10-13

Bighorn Mountains, WY
2015
  ortho_1-1_hn_s_wy019_2015_2.sid Johnson 2015-09-12

Teton Range
2006
  ortho_1-1_1n_s_wy039_2006_1.sid Teton   2006-09-02
2015
  ortho_1-1_hn_s_wy035_2015_2.sid Sublette 2015-09-09 to 2015-10-13
  ortho_1-1_hn_s_wy039_2015_2.sid Teton   2015-09-12 to 2015-09-22
2019
  ortho_1-1_hn_s_wy039_2019_1.sid Teton   2019-07-20 to 2015-09-22

Wind River Range
2006
  ortho_1-1_1n_s_wy035_2006_1.sid Sublette 2006-09-02
2015
  ortho_1-1_hn_s_wy013_2015_2.sid Fremont 2015-09-09 to 2015-10-13
  ortho_1-1_hn_s_wy035_2015_2.sid Sublette 2015-09-09 to 2015-10-13
2019
  ortho_1-1_hn_s_wy013_2019_1.sid Fremont 2019-07-20 to 2019-08-27
  ortho_1-1_hn_s_wy035_2019_1.sid Sublette 2019-08-15 to 2019-09-13

758

759

760 **Table A18.** List of dates of the Maxar imagery used for outlining glaciers and perennial
761 snowfields in Wyoming.

Region/ Date (Year-M-D)

Wind River Range

  2018-09-06

762

763

764 **8. Author Contributions.**

765

766 Andrew G. Fountain was the principal investigator of the project, he wrote the proposal and
767 digitized glacier and snowfield outlines, analyzed the data, and led the writing of this report.
768 Bryce Glenn was the GIS expert responsible for the geographic format (e.g. projection,
769 attributes, database structure) and quality control. He digitized glacier and snowfield outlines,
770 analyzed the data, and helped write the report. Chris McNeil provided some of the imagery.

771

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784

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