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 ± 14.34 km^2) glaciers, 1776 (31.01 ± 9.30 km^2) perennial snowfields, and 35 (3.57 km^2 ± 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 & 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 & 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 & 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 & Hock, 2018; Pritchard, 2019). Globally, the loss of perennial ice from the landscape is a major contributor to sea level rise (Meier, 1984; Parkes & 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

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

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

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

2. Methods

2.1 Data Sources, Classification, Digitizing, and Completeness

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

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

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

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

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

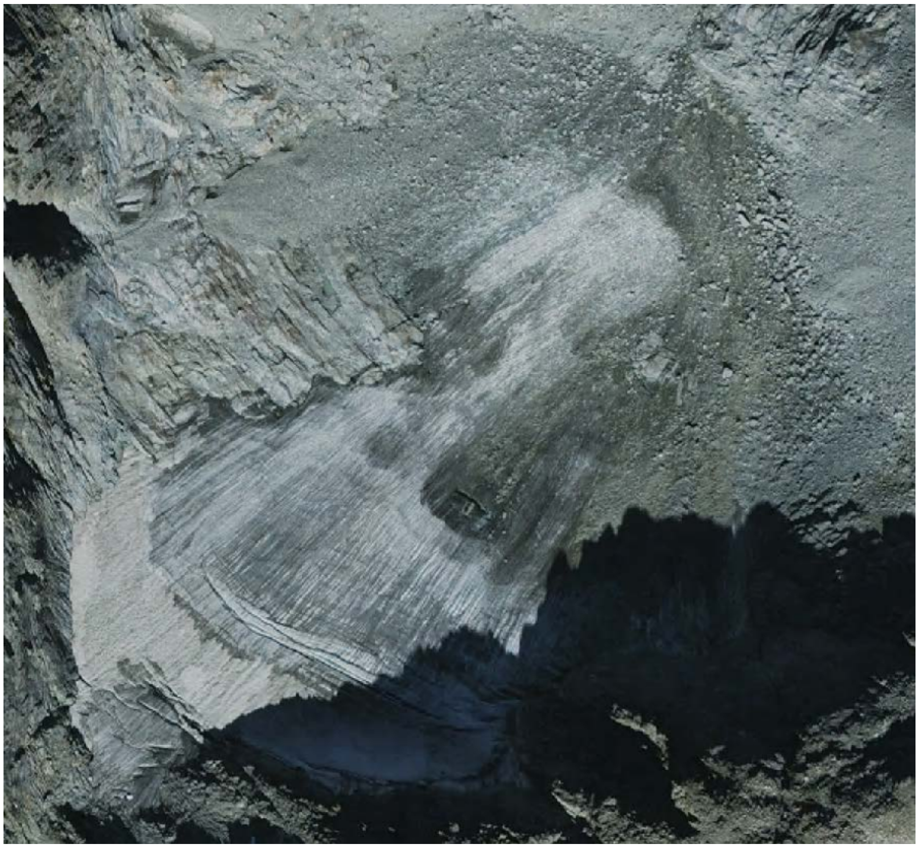

Figure 1. An example of a glacier seemingly melting into the talus surrounding the terminus (upper right). The glacier is flowing from the lower left-hand corner to the upper right-hand corner. The glacier is located in the Wind River Range, WY, INV_ID E618081N4774579 and base image is from the National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

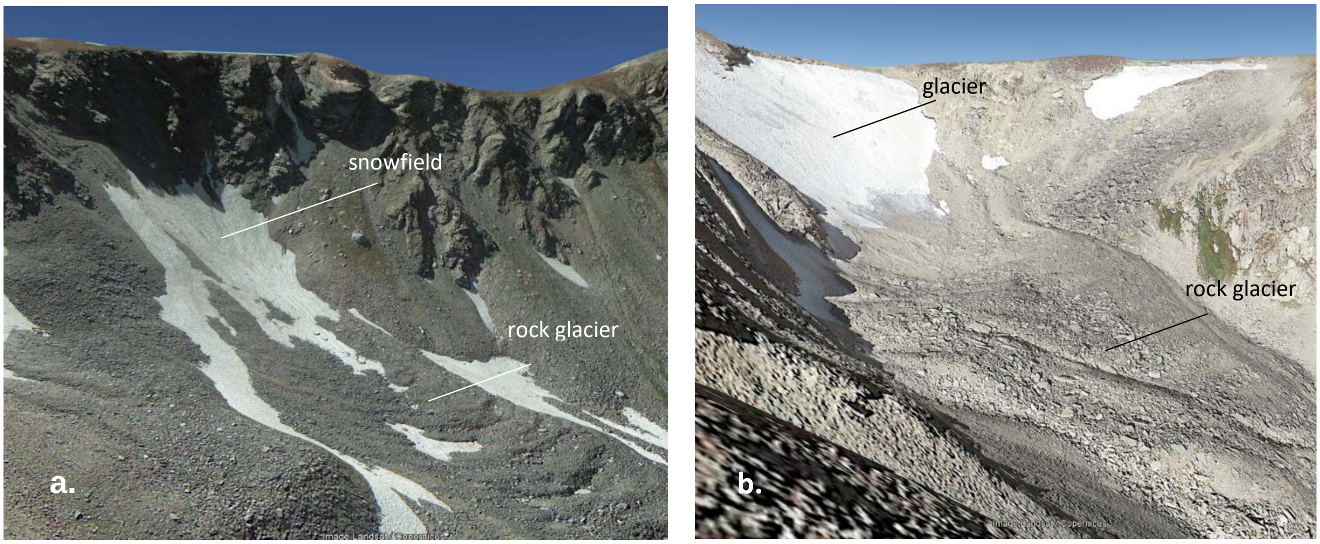

Figure 2. Examples of glacier versus rock glacier identification. (a) An example of a snowfield that is considered part of the rock glacier. Location, Colorado Front Range, 40.827477° N, -106.657400° E. Image is from © Google Earth, 9/2014; (b) Tyndall Glacier in the Colorado Front Range, 40.305291° N, -105.689602° E, with a rock glacier slightly down valley. Image is from © Google Earth 9/2016.

In a number of situations, we observed buried ice adjacent to a glacier (Figure 3). Here we use the term 'buried ice' to mean dead ice formerly part of a flowing glacier, and not the permafrost context of ice embedded within or on top of perennially frozen ground. The rocky surface texture of the buried ice was hummocky and very different from surrounding bedrock and adjacent ice, and not a moraine. Occasionally a crack in the surface revealed subsurface ice. The feature appeared to be non-moving (dead) ice that is covered by debris similar to some of the ice-debris complexes described by Bolch et al. (2019). We decided to include these features as a separate classification, 'buried ice', because their size was large relative to the glacier, they were probably once part of the glacier, and may be important local sources of meltwater for streamflow.

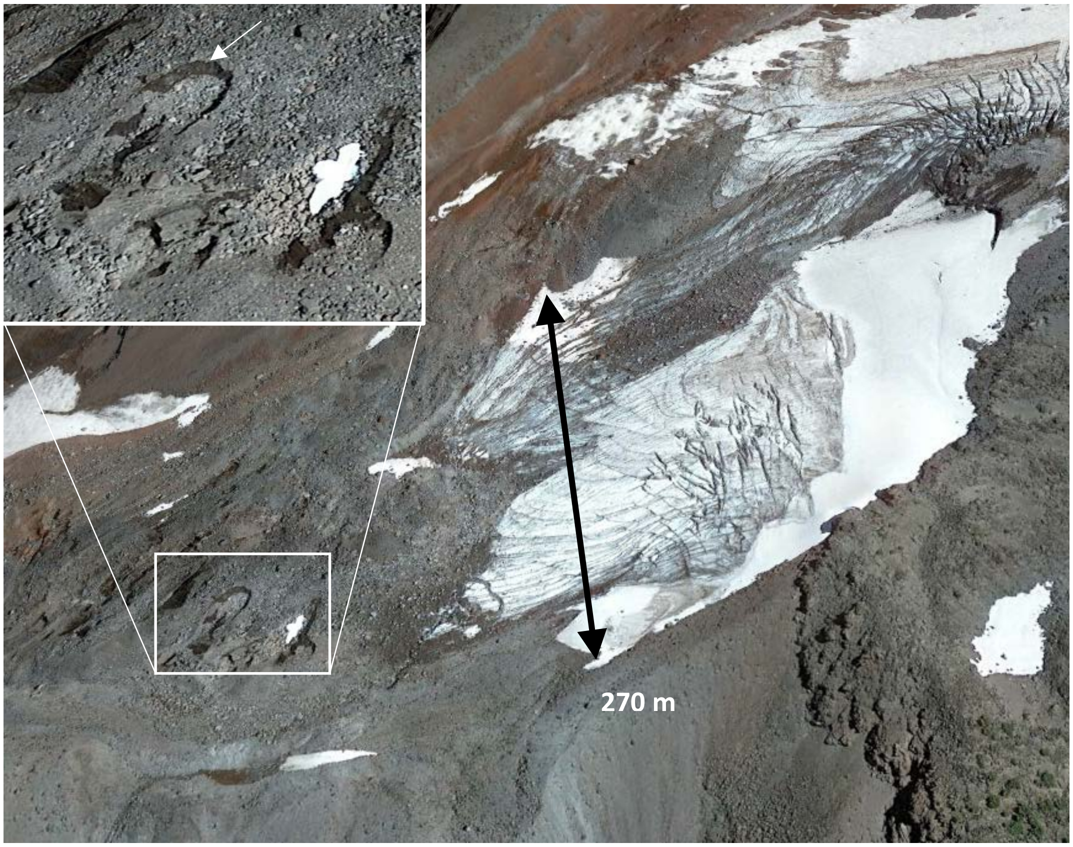

Figure 3. Lost Creek Glacier, South Sister, Oregon. Note buried ice and lack of crevasses to the left of the grey-blue ice, suggesting ice that is no longer moving and therefore not part of the dynamic glacier. The white box surrounds an area that has collapsed due to subsurface melt. The inset enlargement 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 differences in methods. Buried-ice features were eliminated from our inventory because the SFI did not map buried ice. The SFI was filtered to only include features ≥ 0.01 km^2 to match our minimum area threshold; a small number of features located in Canada were removed; and a few mis-classifications of ponds, lakes and dry lakebeds as glaciers were removed. Notably, the SFI did not split contiguous ice masses, such as glacier-covered volcanoes, into individual glaciers, consequently we do not expect the number of features in the SFI and our inventory to match. Once the two inventories were reconciled, those glaciers and perennial snowfields unique to one inventory were examined for inclusion in a revised inventory. Features selected from the SFI were digitized using the same imagery we used for our inventory.

The revised inventory was then compared to the 2016 National Land Cover Database (NLCD, Dewitz, 2019), which did not map glaciers and perennial snowfields per se, but mapped the distribution of perennial snow and ice (Jin et al., 2019; Wickham et al., 2021). However, the NLCD used a small number of recent images to assess a 'perennial' presence and therefore significant errors of commission are expected. Also, the landscape class of snow and ice received less attention than other classes (e.g. agriculture) such that the timing of imagery acquisition may be earlier in the summer than optimal and misclassification of clouds as snow and ice may be present (personal communication C. Homer and J. Dewitz, USGS, email December 2015). The NLCD inventory was compared to the revised inventory and, as before, the features unique to one inventory were examined for inclusion. Those features selected from the NLCD for inclusion were digitized using the same imagery we used for our inventory.

2.2 Uncertainty

Three main sources of uncertainty in the glacier outlines, are georeferencing, digitization, and interpretation (DeVisser & Fountain, 2015; Sitts et al., 2010). We found georeferencing error to very small. In any case, the precise location of the outline does not affect its area. Also, the digitized points are highly correlated such that no deviations from the true outline are caused by georeferencing. Digitizing error is relatively small, 1%, with good imagery and crisp contrast between the glacier and ice-free surroundings (DeVisser & Fountain, 2015; Hoffman et al., 2007). The largest uncertainty is interpretation error caused by poor imagery, shadow, debris cover, and seasonal snow patches. This uncertainty was calculated in different ways according to the situation. If the outline was digitized a second (or third) time due different interpretations by the authors or collaborators the uncertainty is one-half the absolute difference of the between the largest and smallest digitized areas (the range) divided by the final area and expressed as a percentage. For the relatively few glaciers where a small section of perimeter was masked by deep shadow, seasonal snow patches, rock debris, or poor imagery, a higher uncertainty was assigned by visually estimating the area in question and dividing by the total possible area. In a few cases the location of a flow divide between glaciers wasn't clear a 5% error is assigned. This was calculated from the area difference in several test cases where multiple possible flow divides were digitized. For perennial snowfields, the smaller patch of perennial snow is often covered by seasonal snow, which varies greatly from year to year. We measured the area of a number of snowfields over time using late summer historic imagery in Google Earth. Results showed that the variations in snowfield area could be as much as 30%. We assigned this somewhat arbitrary uncertainty in order to note snowfield presence and location, but preclude them from area change calculations because area differences are typically smaller than the assigned uncertainty.

3. Results

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

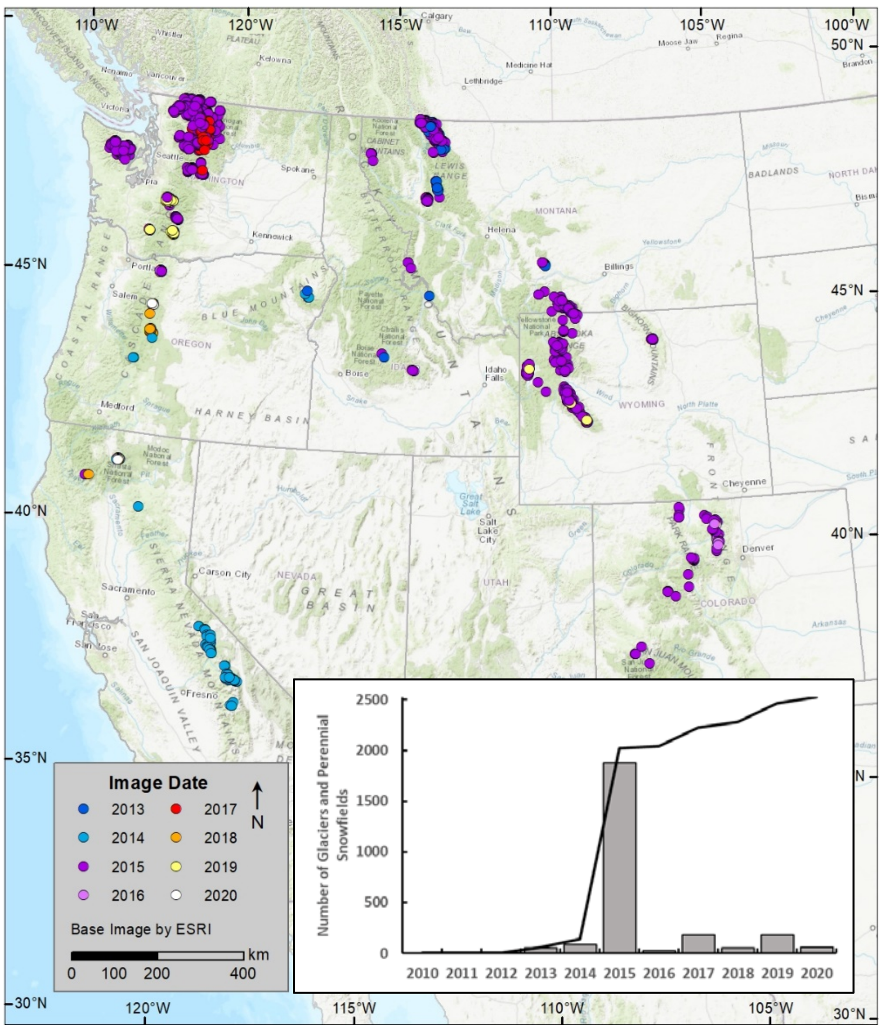

Figure 4. The spatial distribution and number of glaciers and perennial snowfields, greater than 0.01 km^2, in the western United States. Colors indicate the date of aerial and satellite imagery used to outline the features. The line is the cumulative total. Base imagery from Esri Inc. Inset is a bar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

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

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

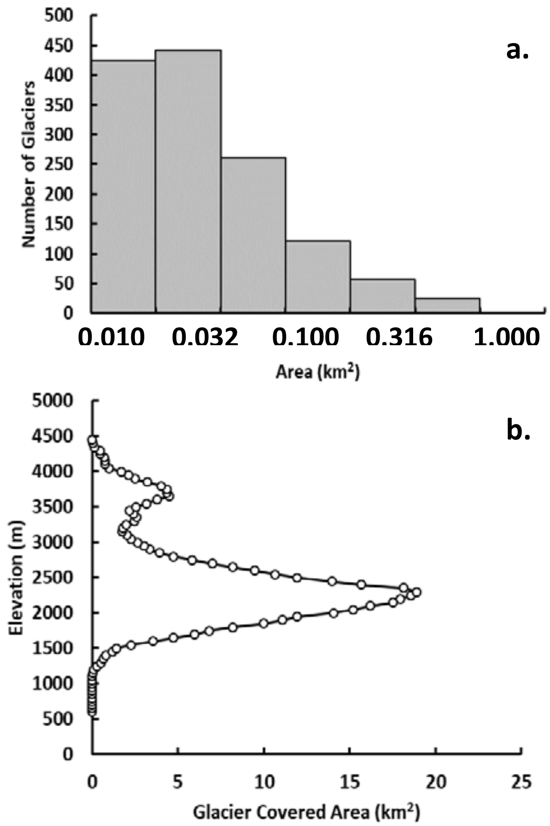

Figure 5. The area and elevation distribution of glaciers in the western U.S., (a) Histogram showing the number of glaciers as a function of area. The x-axis intervals are log intervals; (b) Elevation distribution of glacier-covered area.

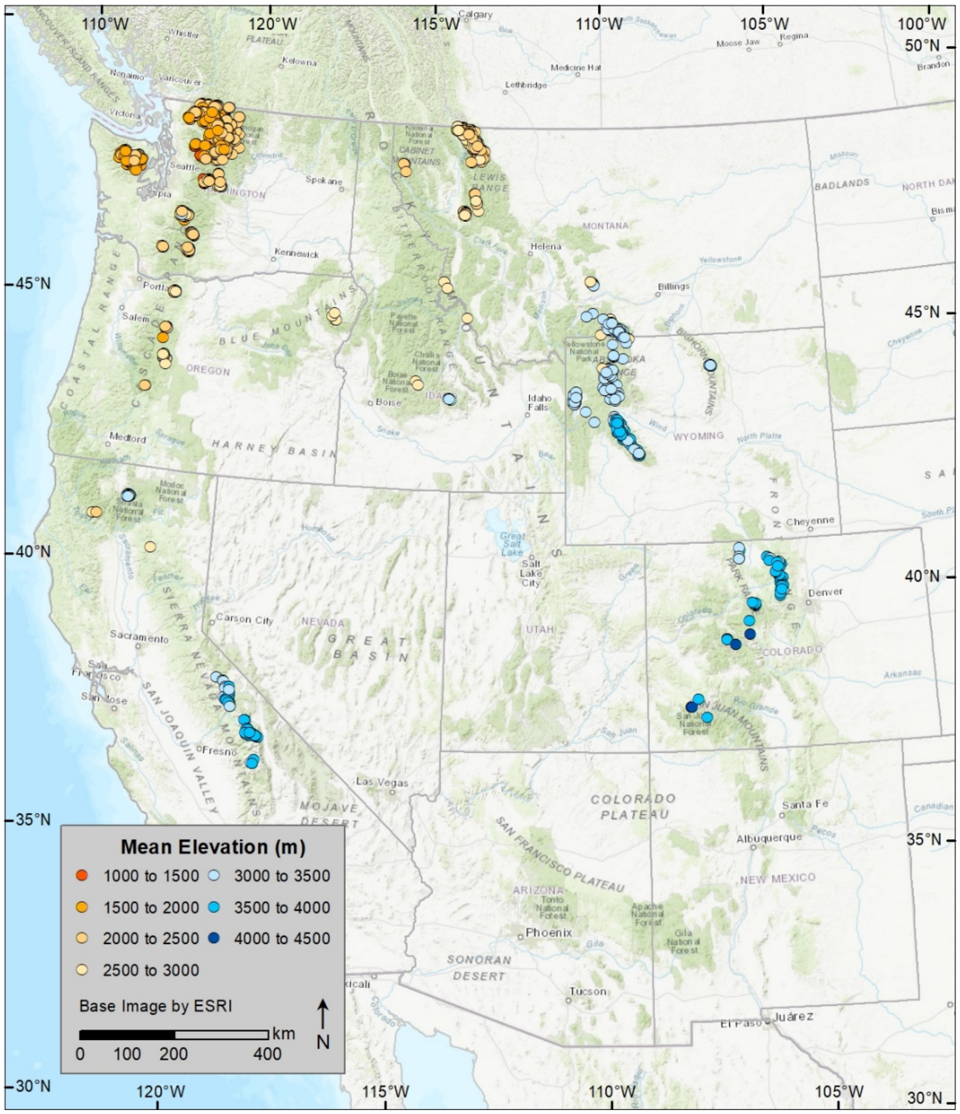

Figure 6. Elevation distribution of glaciers and perennial snowfields across the western US. Base imagery from Esri Inc.

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.

4. Discussion

The advent of relatively frequent high resolution (≤ 1 m) optical aerial and satellite imagery available at little or no cost has made compiling and updating glacier inventories a realistic opportunity. Finding suitable imagery spanning only a few years apart provides a near-snapshot of glacier cover. This contrasts strongly with mapping efforts only a few decades ago when aerial-only photographic surveys required decades to cover the western US (Gesch et al., 2002). And the advent of GIS software made digitizing, summarizing, and interrogating digital outlines practical.

We had used the Fountain et al., 2017 historic inventory as a template to locate and update the perimeters of all the glaciers and perennial snowfields. Considering that the inventory was derived from the U.S. Geological Survey 1:24,000 maps, a result of a national effort to remap the entire country at a higher resolution, we were a surprised that 240 features (~10%) were missed. These missing features were revealed after comparison with two other independently derived inventories. We had a similar experience in a prior study when comparing two independently derived glacier inventories. Together they suggest that independent efforts are important to compiling a comprehensive inventory.

Multiple checks more accurately define glacier perimeters (Leigh et al., 2019). Different investigators may make different decisions about glacier boundaries and results can differ particularly in debris-covered conditions or along flow divides (Paul et al., 2013). When they agree, it provides some confidence of the interpretation accuracy and where they disagree it provides input for estimating interpretation error.

The total area of glaciers in the western US, 367 km^2, is a little smaller than that in Austria, 415 km^2, (Fischer et al., 2015). Like glacier populated regions elsewhere the distribution of glacier area is skewed towards smaller glaciers (e.g. Linsbauer et al., 2012; Mishra et al., 2023; Zalazar et al., 2020). The uncertainty in glacier area is also similar with an overall 5% uncertainty for the total area. Paul et al. (2020) report an uncertainty of 3.3% over a set of 15 glaciers, 4% for 7 glaciers (Zalazar et al., 2020), 2.3% for 15 glaciers (Linsbauer et al., 2021). Our assessment method differs from those cited here in that we estimate the uncertainty for each individual glacier rather than upscaling the uncertainty calculated for a small subsample.

5. Data products and availability

The data are available in three formats. The geospatial data and attribute tables are available in the shapefile (Esri) format and in an open source GeoJSON format. The attribute table is also available as an EXCEL file. These data products can be obtained from https://doi.org/10.15760/geology-data.03 (Fountain & Glenn, 2022) and from the Global Land Ice Measurements from Space website http://glims.colorado.edu/glacierdata/. Maxar imagery was accessed through the USGS and NGA NEXTVIEW license. The Maxar imagery has limited availability owing to restrictions (proprietary interest). Contact cmcneil@usgs.gov for more information.

6. Conclusions

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

7. Appendix A

A1 Missing Glaciers

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

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

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

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

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

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

A4 Notes on imagery and interpretation challenges by State.

This appendix, organized by US State, then by mountain range, summarizes the specific imagery used, challenges encountered in feature identification and outline digitization. The Selkowitz and Forster (2016) inventory is referred to as the SFI and the National Land Cover Database inventory (Dewitz, 2019) is referred to as the NLCD.

A4.1 California

Imagery and DEMs used are listed in Tables A4, A5, A6.

Cascade Range

Mount Shasta

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

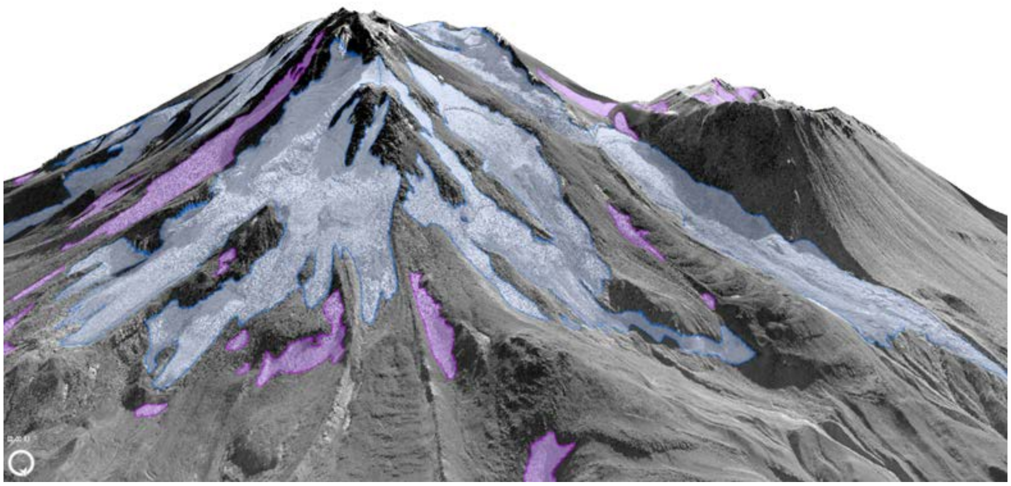

Figure A1. Mt. Shasta glaciers in bluish white, perennial snowfields/ice patches in lavender draped over a 3D rendering created from 2010 lidar (Robinson, 2014).

Sierra Nevada

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

Trinity Alps

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

Table A4. List of NAIP imagery used for outlining glaciers and perennial snowfields in California. '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)
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

Table A5. List of dates of the Maxar imagery used for outlining glaciers and perennial snowfields in California.

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

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

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

A4.2 Colorado

The 2015 NAIP was generally free of seasonal snow. Where it persisted at the terminus of a few 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		
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

A4.3 Idaho

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

Table A8. List of NAIP imagery used for outlining glaciers and perennial snowfields in Idaho. ‘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)
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

A4.4 Montana

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

Beartooth-Absaroka Range

The 2015 NAIP imagery was the best overall imagery due to the least snow, but Google Earth was occasionally used as well. Google Earth had imagery dated to 9/11/2015; often with less seasonal snow than the NAIP imagery. To counter any mismatch in projection, outlines digitized in Google Earth were imported to ArcGIS and projected to match the NAIP projection.

Bitterroot Range

No features were mapped in the Bitterroot Range by the USGS (Fountain et al., (2017). One glacier and three perennial snowfields were added based on the NLCD.

Cabinet Range

The USGS mapped four features ≥ 0.01 km^2 (Fountain et al., 2017). Inspection of the 2015 only one was ≥ 0.01 km^2. Seven glaciers and perennial snowfields were added; five were identified in our initial inventory, the other two were identified by the SFI and NLCD, respectively. All were less than 0.05 km^2.

Crazy Mountains

The 2013 NAIP imagery was the best imagery available and included limited seasonal snow. The 2019 Maxar imagery had too much seasonal snow.

Lewis Range (Glacier National Park)

The most recent published glacier inventory is a 2015 USGS inventory (Fagre et al., 2017). They outlined the main-body of named-glaciers using 2015 Maxar imagery. We digitized the outlines of all glaciers and perennial snowfields using 2015 Maxar imagery where available. Elsewhere, 2015 and 2013 NAIP imagery were used; both years had lots of seasonal snow cover. Two major glaciers, Blackfoot (Figure A2) and Harrison (Figure A3) glaciers, separated into pieces as it retreated since it was originally mapped by the USGS (Fountain et al., 2007).

Madison Range

The 2013 NAIP imagery was the only imagery used due to extensive snow in the other years. No glaciers or perennial snowfields were found. Of the two features ≥ 0.01 km^2 mapped by the USGS (Fountain et al., 2017), the 2013 imagery showed that one feature is a rock glacier and the other was less than 0.01 km^2.

Mission-Swan-Flathead Ranges

Based on the least snow cover, the 2013 NAIP was better in the Mission and Flathead Ranges, and the 2015 NAIP was better in the Swan Range. No glaciers or perennial snowfields remain in the Flathead Range.

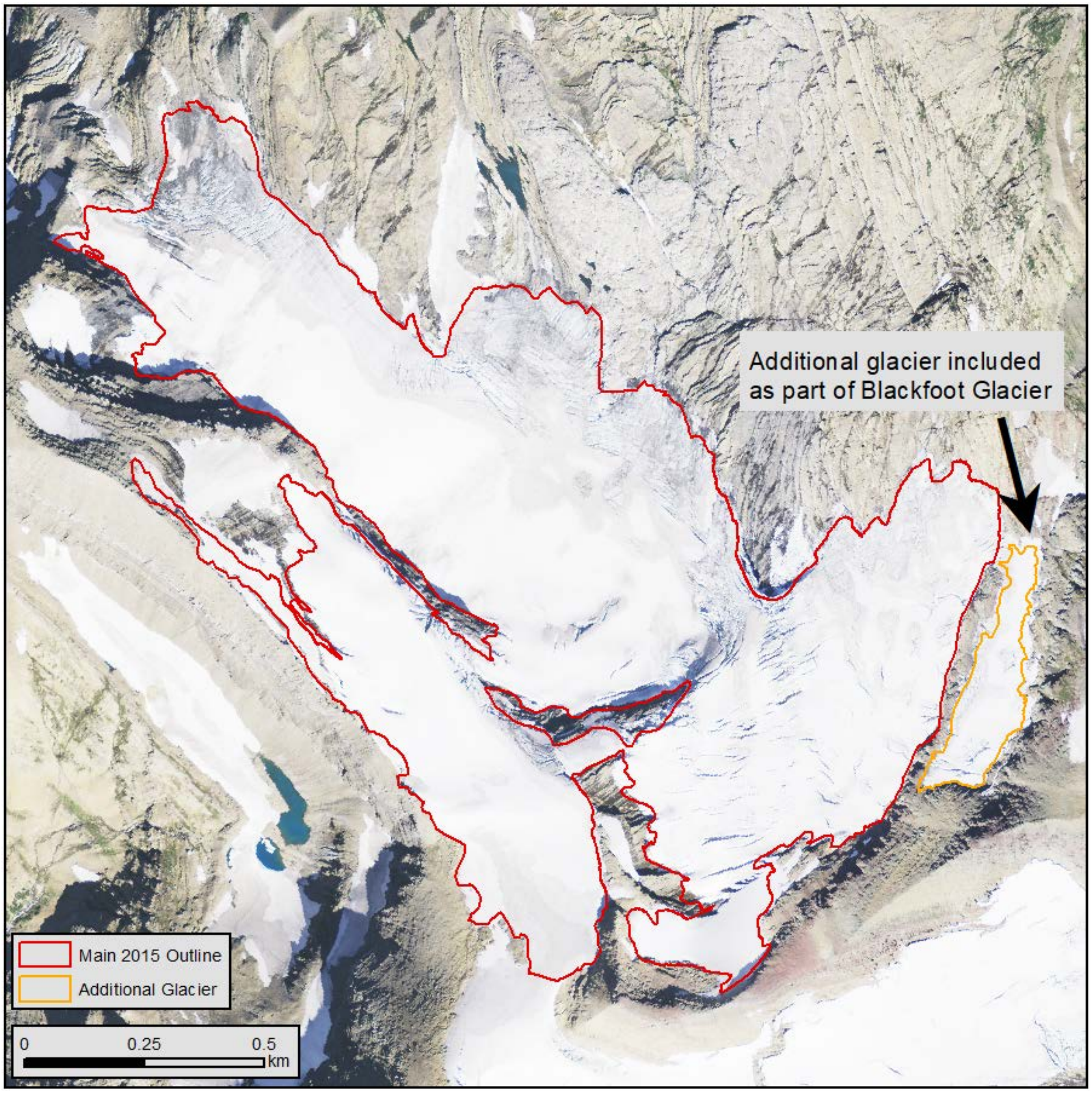

Figure A2. The updated (2015) outlines for the Blackfoot Glacier including the main glacier body (red) and the additional smaller glacier (orange). Base image from the NAIP taken in 2013.

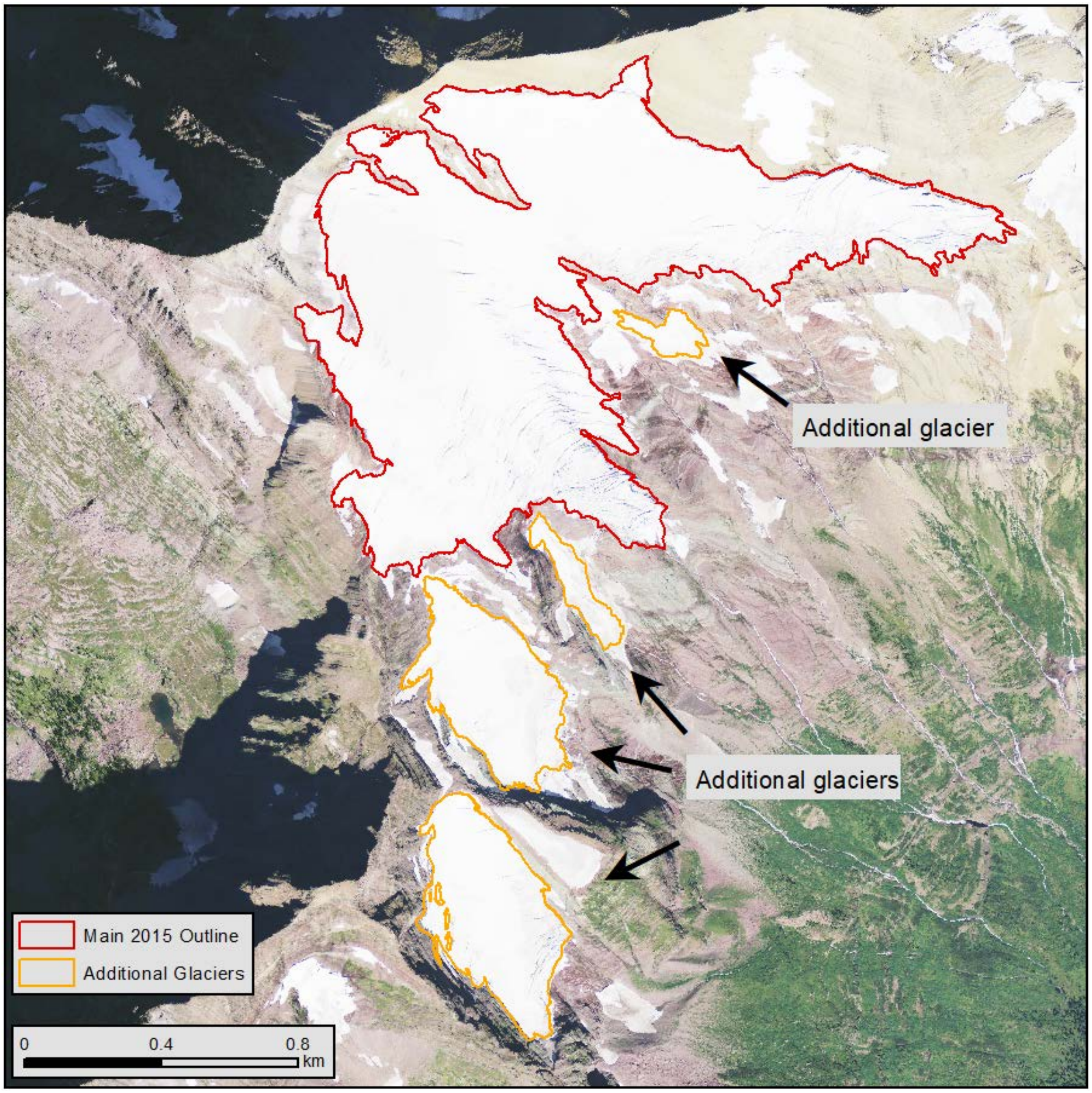

Figure A3. The updated (2015) outlines for Harrison Glacier including the main glacier body (red) and the additional smaller glaciers (orange). Base image from the NAIP taken in 2013.

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

Table A10. List of dates of the Maxar imagery used for outlining glaciers and perennial snowfields in Montana.

Region/ Date (Year-M-D)
Lewis Range
2015-08-22
2015-09-01
2015-09-12
2015-09-25
2019-08-20

A4.5 Oregon

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

Cascade Range

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

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

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

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

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

Wallowa Mountains

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

Table A11. List of NAIP imagery used for outlining glaciers and perennial snowfields in Oregon. '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)
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

Table A12. List of dates of the Maxar imagery used for outlining glaciers and perennial snowfields in Oregon.

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

Table A13. List of Oregon Department of Geology and Mineral Industries digital elevation models used for outlining glaciers and perennial snowfields in Oregon.

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

A4.6 Washington

The 2015 NAIP imagery was typically excellent with little snow cover, whereas the 2017 NAIP had more snow and the 2019 imagery had lots of snow. For most outlines, 2015 NAIP imagery was used. In some places, the 2017 NAIP imagery had less snow and was used instead. Maxar imagery was of limited use and often wasn't better than the 2015 or 2017 NAIP. Tables A14, A15, A16, list the imagery and DEMs used.

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 week from the time of imagery.

Mount Adams

No suitable NAIP imagery was found, instead 2019 Maxar imagery was used. In addition to the Maxar imagery, a multidirectional hillshade and 3-m contour lines derived from a 2016 lidar DEM (Bard 2019) were used as a guide when delignating flow divides. Occasionally, 2009 Google Earth imagery was also useful. Extensive snow covered the mountain when the 2016 lidar was flown masking some of the glacier termini. However, the DEM was helpful in correcting the imagery where poorly aligned with the terrain.

Multiple buried-ice features were identified near the terminus of several glaciers where ice appeared to have decoupled from the main active glacier. Large areas below the glaciers (Mazama, Adams, and Pinnacle) likely have debris-covered ice. We focused on the features which were likely to contain ice based on meltwater streams exiting near the features and hummocky terrain which appeared to indicate melt. Ground-based images from taken between 2014 to 2018 helped decision-making. The images were particularly helpful in identifying a debris-covered ice cliff at Adams Glacier.

Mount Rainier

In general, the 2019 NAIP and the Maxar (2018-09-25) were used for the outlines. Although the GNIS includes the Nisqually Icefall as a separate feature, we included the icefall as part of the Nisqually Glacier (Figure A4).

Mount St. Helens

We used a GIS layer of geological mapping units that included snow and ice from the USGS (David Sherrod, USGS written communication, 2021) to help guide our search. The Crater Glacier (INV_ID E562842N5115499) was heavily debris covered, and obscured by shadow in some areas.

Olympic Mountains

A 2015 inventory of the region was compiled because more recent imagery (NAIP and Maxar) were not useful due to seasonal snow. Our updated inventory differs from that published in Fountain et al. (2017) in two ways. First, they outlined and grouped the glaciers and perennial snowfields according to watershed rather than individual glacier. Their goal was to estimate glacier change relative to a previous study by Spicer (1986) and had to follow Spicer’s approach. Second, all outlines were rechecked and compared to SFI and the NLCD resulting in minor changes.

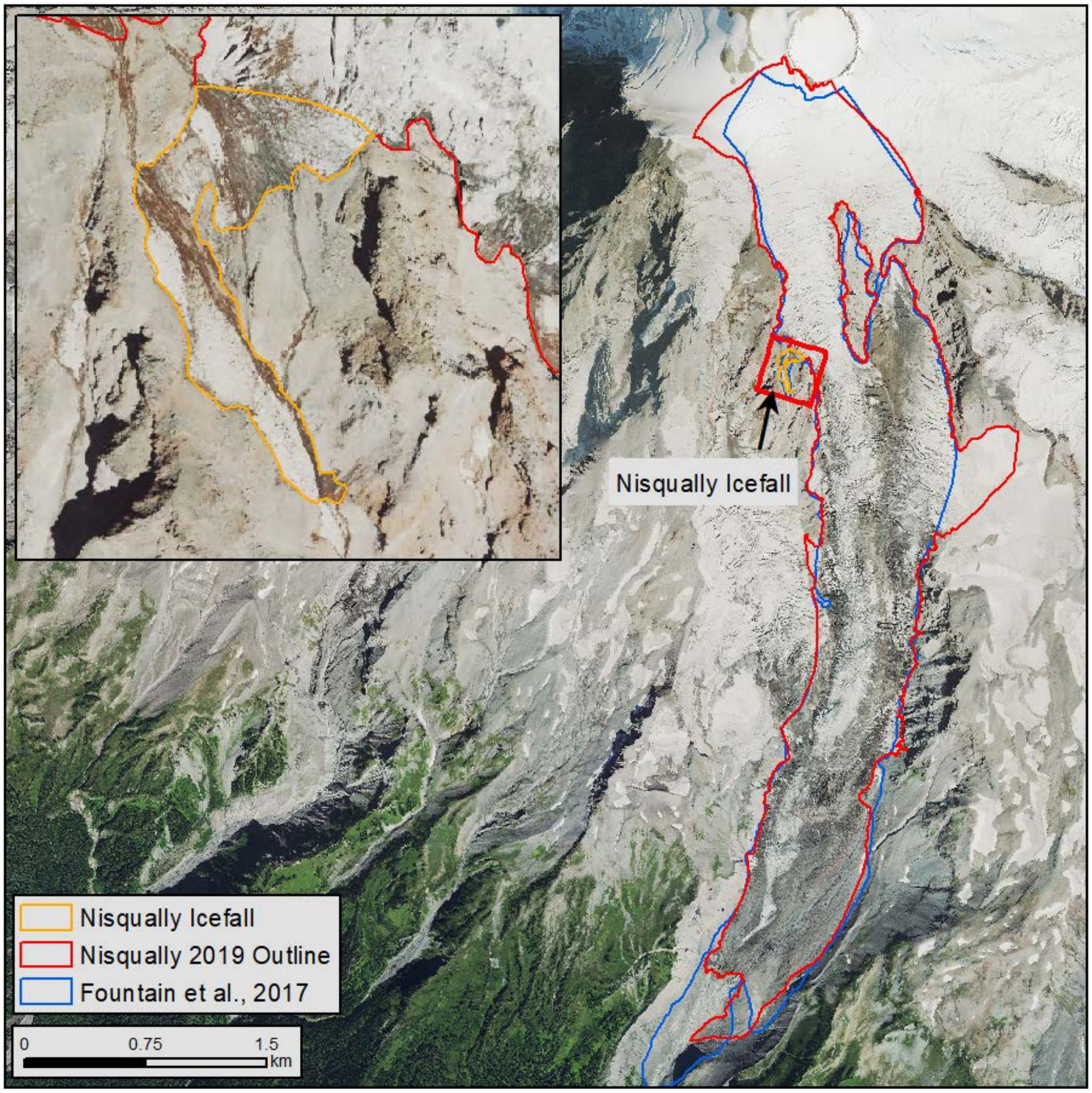

Figure A4. Image of the Nisqually Glacier and Icefall. The orange and red outlines are from the updated inventory and the blue outline is from the USGS mapping (Fountain et al., 2007) database. The base image is from the NAIP taken in 2019.

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 and perennial snowfields in Washington. To access the data both the URL and specific identifier 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

A7 Wyoming

Wind River Range

Tables A17 and A18 list the imagery used. The 2015 NAIP imagery had little snow in contrast to 2019 imagery. Shadows are common in the 2015 imagery and can be very dark. Occasionally the 2019 imagery was used to define the glacier-bedrock headwall boundary. The 2019 Maxar imagery was essentially identical to the NAIP and because its black and white not as useful. Imagery from 2017 and 2018 were a bit too snowy around the glacier margin to be useful. The 2018-09-06 Maxar imagery covered the entire range, with some clouds.

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

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

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

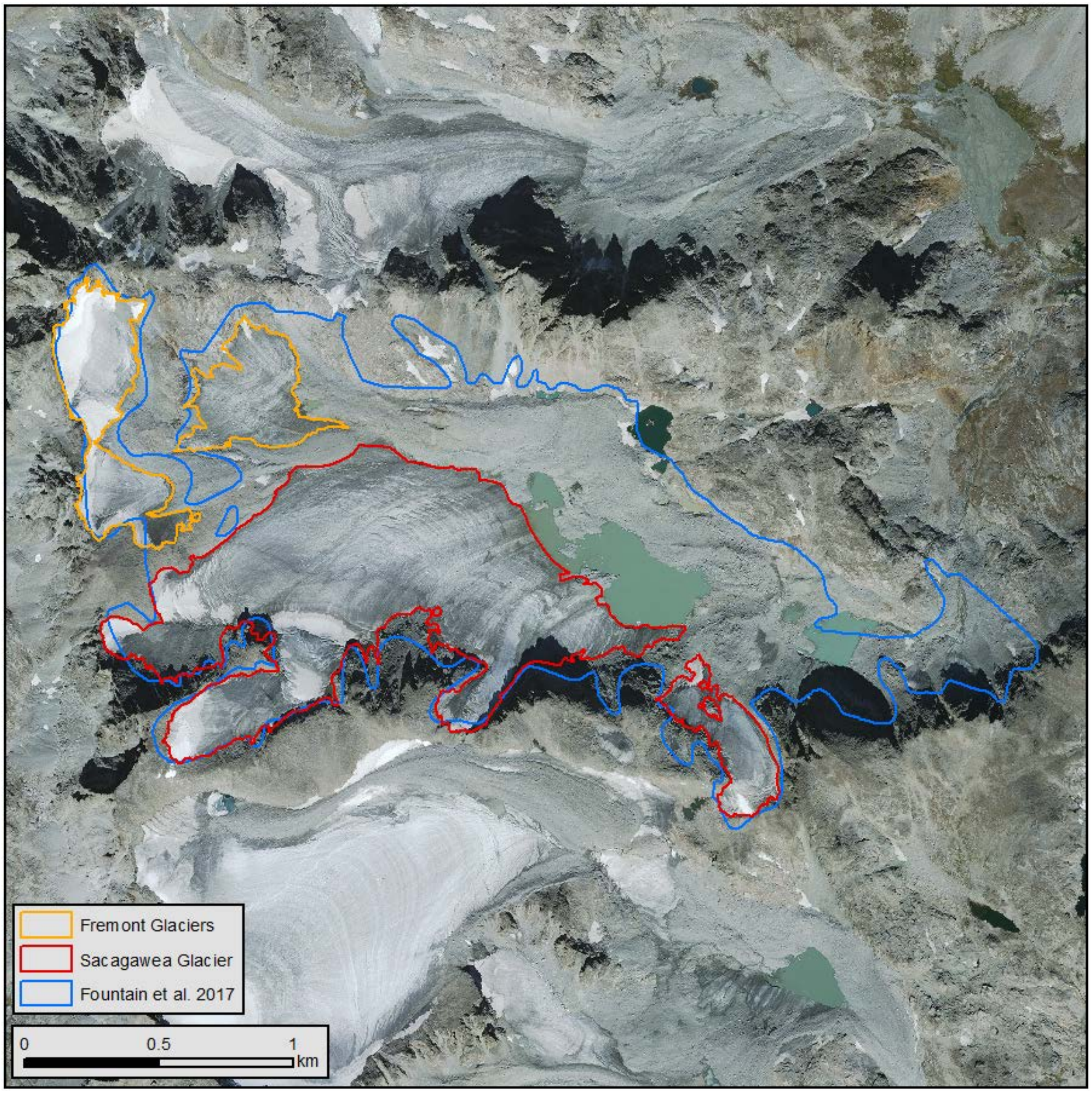

Figure A5. Image of Fremont Glaciers and Sacagawea Glacier showing the Sacagawea outline from the Fountain et al. (2017) database (blue), our updated Fremont Glaciers outlines (orange), and updated Sacagawea outlines (red). The base image is from the NAIP, taken in 2015.

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

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

Region/ Date (Year-M-D)
Wind River Range
2018-09-06

8. Author Contributions.

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

9. Competing Interests.

The authors declare that they have no conflict of interest.

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