8-2017

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Citation Details

Fountain, A. G., Glenn, B., & Basagic IV, H. J. (2017). The geography of glaciers and perennial snowfields in the American West. Arctic, Antarctic, and Alpine Research, 49(3), 391-410.

Arctic, Antarctic, and Alpine Research, Vol. 49, No. 3, 2017, pp. 391–410
DOI: http://dx.doi.org/10.1657/AAAR0017-003

The geography of glaciers and perennial snowfields in the American West

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ABSTRACT

A comprehensive mid-20th century inventory of glaciers and perennial snowfields (G&PS) was compiled for the American West, west of the 100° meridian. The inventory was derived from U.S. Geological Survey 1:24,000 topographic maps based on aerial photographs acquired during 35 years, 1955–1990, of which the first 20 years or more was a cool period with little glacier change. The mapped features were filtered for those greater than 0.01 km^2. Results show that 5036 G&PS (672 km^2, 14 km^3) populate eight states, of which about 1276 (554 km^2, 12 km^3) are glaciers. Uncertainty is estimated at ±9% for area and ±20% for volume. Two populations of G&PS were identified based on air temperature and precipitation. The larger is found in a maritime climate of the Pacific Northwest, characterized by warm winter air temperatures and high winter precipitation (~2100 mm). The other population is continental in climate, characterized by cold winter air temperatures, relatively low winter precipitation (~880 mm), and located at higher elevations elsewhere. The G&PS in the Pacific Northwest, especially in the Olympic Mountains, are particularly vulnerable to warming winter air temperatures that will change the phase of winter precipitation from snow to rain, further accelerating glacier shrinkage in the future. Comparison with a recent inventory suggests that the total G&PS area in the American West may have decreased by as much as 39% since the mid-20th century.

INTRODUCTION

Glaciers are an important feature of the landscape. In temperate zones they are agents of erosion and deposition and modify the landscape in dramatic ways (Kleman, 1994; Benn and Evans, 2010; Thomson et al., 2010). Hydrologically, glaciers naturally regulate streamflow on seasonal to decadal time scales (Fountain and Tangborn, 1985; Jansson et al., 2003). Glaciers act as frozen reservoirs that increase melt and runoff during warm periods and keep stream temperatures cooler during the driest and hottest part of the summer when rainfall is minimal and seasonal snowpacks have vanished. Thus, watersheds with glaciers have more reliable runoff than ice-free watersheds with a minimum variability when one-third of the watershed is covered by ice (Fountain and Tangborn, 1985; Fleming and Clarke, 2005; Moore et al., 2009). Smaller glaciers have less ability to buffer seasonal runoff variations, and watersheds become more subject to drought (Hall and Fagre, 2003; Moore et al., 2009). The loss of resident ice on the landscape is a major contribution to sea level rise (Meier, 1984; Radić et al., 2014).

Glacier inventories provide a snapshot of ice cover across a landscape and have been valuable tools for assessing glacier contribution to sea level change (Radić and Hock, 2010; Pfeffer et al., 2014), to regional hydrology (Yao et al., 2007; Moore et al., 2009), and for assessing high alpine erosion (Mitchell and Montgomery, 2006; Barr and Spagnolo, 2014). An inventory also provides a baseline against which future changes can be assessed. In this era of climate warming and accelerated glacier recession, inventories provide a basis for estimating the future of stream flow contributions from glaciers, including both those from net mass loss (glacier wastage) and those from the annual cycle of seasonal melt. Detailed glacier inventories have been compiled for many regions of the world (Mool et al., 2001; Williams, Jr., and Ferrigno, 2005; Fischer et al., 2014; Pfeffer et al., 2014). An exception has been the American West, defined here as those states west of the 100th meridian, including Washington, Oregon, California, Idaho, Utah, Nevada, Montana, Wyoming, and Colorado. Despite a vigorous history of studies on individual glaciers (e.g., Armstrong, 1989; Rasmussen, 2009) and their glacial geology (Davis, 1988; Bowerman and Clark, 2011; Osborn et al., 2012), this region has not been subject to a rigorous glacial inventory.

The earliest scientific discussion of glaciers across the American West identified some of the glacier-populated regions and summarized observations of a few glaciers (Russell, 1897). The first enumeration of the glaciers (Meier, 1961) summarized glacier areas for each state based on generalized estimates, the sources for which are obscure. Denton (1975) provided a relatively detailed inventory, summarized previous studies, and identified specific glaciers, but did not tabulate glacier area. Krimmel (2002) enlarged Denton's study but did not improve on the enumeration of glaciers or glacier area. The most recent study (Selkowitz and Forster, 2016) inventoried the number and area of glaciers and perennial snowfields using Landsat imagery with an automated detection scheme. Regional glacier inventories have been compiled for the North Cascades and Olympic Mountains, Washington; and the Sierra Nevada, California (Post et al., 1971; Spicer, 1986; Raub et al., 2006). The tabular data summarized in these inventories are detailed; however, the mapped glacier outlines are generalized to fit the scale of the paper maps and therefore are not useful for specific comparison with later glacier outlines.

An often overlooked category is perennial snowfields. Typically smaller than glaciers, perennial snowfields do some geomorphic work as nivation hollows (Thorn, 1976; Rapp et al., 1986) and pattern alpine plant communities (Walker et al., 1993). They may be important sources of water in late summer in locations where glaciers are few (Shook and Gray, 1997). With regard to archaeology, snowfields have become important in recent years because of the abundance of artifacts often found along their perimeters (Beattie et al., 2000; Lee, 2012). Presumably, large game animals such as elk used the snowfields as refuges from insects and drew the attention of prehistoric hunters to these features.

The purpose of this report is to describe the geography of glaciers and perennial snowfields in the American West for the mid-20th century. This paper does not attempt to document all the past studies on glaciers throughout this region, of which there have been many, but it is focused on providing a rigorous compilation of glacier and snowfield distributions, their topographic characteristics, and the climate conditions in which they are found. Finally, we estimated the volume of glaciers and perennial snowfields (G&PS). The digital outlines provide a template to aid in the future tracking of glacier change and a datum against which future changes can be compared. The outlines will be made available to the National Snow and Ice Data Center, Boulder, Colorado, for distribution to various global glacier inventories and for other uses.

METHODS

The inventory of G&PS was derived from the U.S. Geological Survey (USGS) 1:24,000 topographic maps that were based on aerial photography (USGS, 1998). The maps were originally produced as hard copy mylar/paper versions and were later digitized by the USGS to produce a 10 m digital elevation model (DEM) and digital outlines of landscape features (Gesch et al., 2002; Fountain et al., 2007). The mapped landscape features included a category for "glaciers and permanent snowfields" (USGS, 2005). Because these mapped features were not field-checked, there is no way to distinguish among them, and we refer to them collectively as G&PS. We prefer to use *perennial* as a more precise descriptor than *permanent* because glaciers and snowfields can disappear. To evaluate the accuracy of the earlier paper maps to digital conversion process, the hard copy maps in digital image form (digital raster graphics) were compared to the digital outlines. Because of the laborious nature of the process, at least two different people independently checked the correspondence—the first checked the correspondence and made adjustments if necessary, and the second checked the updated version.

The completed G&PS outlines were superimposed on the DEM using a geographical information system, and topographic data were calculated including area; maximum, minimum, and mean elevation; slope; and aspect. We recognize that errors in surface elevations may occur where the surface is dominated by snow because of the loss of surface definition during cartographic analysis (Echelmeyer et al., 1996; Arendt et al., 2006). However, the problem is not a major concern because the aerial photography was acquired in late summer when snow in temperate alpine environments is relatively dirty due to the accumulation of eolian transported debris (Thomas and Duval, 1995). Also, the glaciers are generally small with small transport distances from the adjacent ice-free valley walls. Methodological details of acquiring the mapped G&PS are fully described in Fountain et al. (2007).

To investigate the relationship between G&PS location and climate, we superimposed the G&PS polygons over a gridded data set (PRISM) of monthly values of air temperature and precipitation at a cell size of 800 m (Daly et al., 2007). The data were averaged for the winter and summer seasons over the period 1955 to 1990, matching the mapping years. Winter is defined as the months when the mean monthly air temperature is ≤0 °C, and summer is those months when the temperature is >0 °C. These criteria were applied to the climate data defined at the G&PS centroids from all regions yielding six months of winter (November–April) and four months of summer (June–September).

RESULTS

Comparison between the digital outlines and the digital raster images of the paper maps revealed 1243 errors, including missing features (not digitized), poorly digitized or partly digitized outlines, nonglacial features (e.g., lakes) miscoded as glaciers, spurious splits such that a single glacier is split into two parts as if they were separate features, and different glaciers joined into a single feature. The most frequent error was missing features (600), closely followed by errors in glacier perimeter (511). We corrected all errors to conform to the representation on the hard copy maps, and the final data set, derived from the 1:24,000 topographic maps, is referred to as *24K*.

The preliminary inventory identified 8347 G&PS totaling 690.3 km^2 in the eight states of California, Colorado, Idaho, Nevada, Montana, Oregon, Washington, and Wyoming. This number is slightly higher than the 8303 recognized by Fountain et al. (2007) due to an error in the original accounting. The USGS official place names list identifies a "Timpanogos Glacier" on Mount Timpanogos in the Wasatch Range, Utah, but it does not appear on the 1:24,000 USGS topographic maps. Ground-based photos over the past decade show no glacier but instead a seasonal snowfield; we do not include it in the inventory. The aerial photography used to make the maps was acquired over a range of 55 years from 1943 to 1998. Fortunately, very few photographs were acquired before 1955 and after 1990, and this 35-year period accounts for 93% of G&PS and 90% of the total area (Fig. 1). Spot checking the photography showed that seasonal snow was commonly present in patches of variable sizes, sometimes masking part of the glacier outlines.

One might expect significant area changes in the G&PS over the 35 years required for mapping. However, most of the aerial photography was acquired during the mid-20th century cool period when regional air temperatures in the western United States changed little or were cooling slightly, particularly for the first 25 years from 1955 to 1980 (Meehl et al., 2004; Thompson et al., 2008; Ring et al., 2012). Glaciers during this period either stopped retreating or advanced slightly, before resuming a slow retreat in the late 1980s (Conway et al., 1999; Hoffman et al., 2007; Howat et al., 2007; Basagic and Fountain, 2011). We conclude that little net glacier change occurred over the mapping period, which yields a reasonable snapshot of G&PS for the mid-20th century.

The uncertainty of each G&PS area is unknown. The USGS data standards address positional uncertainty and ignore interpretation and digitizing uncertainties (Sitts et al., 2010; DeVisser and Fountain, 2015). We ignored positional uncertainty because the digitized points defining the G&PS parameter are highly auto-correlated and for area assessment the exact position of the feature is unimportant. To estimate area uncertainty, outlines of 55 G&PS in the Sierra Nevada were digitized from the same georectified photographs that were used to construct the original maps. This takes into account both digitizing and interpretation uncertainties. The root mean squared difference between the mapped G&PS outlines and our digitization was ±9%.

Uncertainty was estimated another way using a buffer around each G&PS outline. The buffer was the ground width of the drawn outline on the map, about 12.2 m, and we assumed the actual outline was within that buffer yielding an uncertainty of ±6.1 m. Applying that uncertainty to all the G&PS outlines yielded an average relative uncertainty of ±8% of the area. For individual G&PS the relative uncertainty is larger for smaller features. Taking both approaches into account, we assumed a 9% uncertainty for all G&PS.

Comparison with Regional Inventories

To test the fidelity of the preliminary 24K inventory, which was based on interpretations by cartographers, we compared it against regional inventories based on glaciological expertise. Both approaches relied on one-time aerial photography rather than multiple images of each feature over a number of years. Three detailed regional glacier inventories were compiled by glaciologists using vertical and oblique aerial photography: the North Cascade Range (Post et al., 1971) and Olympic Range (Spicer, 1986), which are both in Washington, and the Sierra Nevada (Raub et al., 2006), which is in California. These inventories were compiled at the 1:62,500 scale.

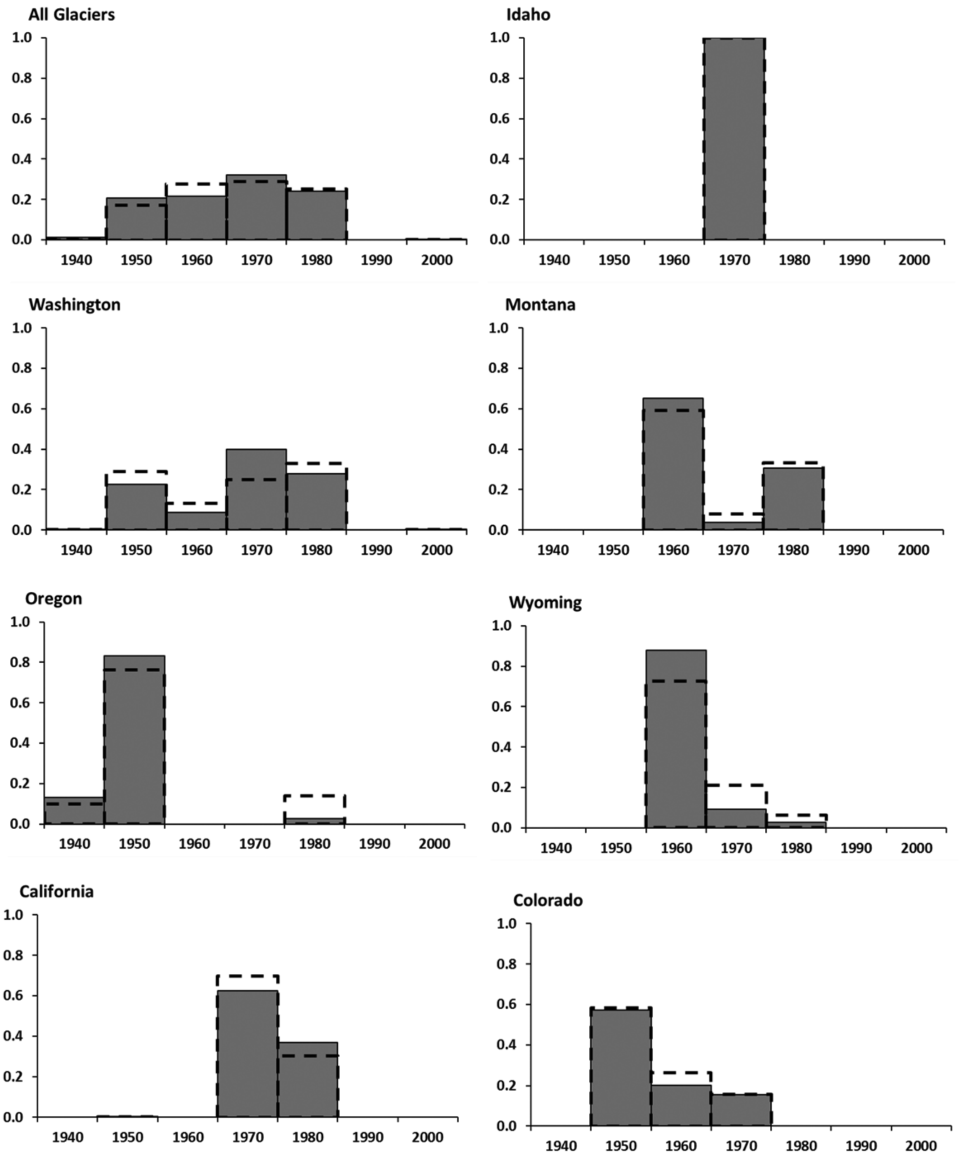

FIGURE 1. **Timing of aerial photograph acquisition used for topographic mapping in regions populated by glaciers and perennial snowfields (G&PS). The *y*-axis is the fraction of total, and the dashed open bars represent the fraction of total number of G&PS; the solid-filled bars represent the fraction of total area. The *x*-axis year represents the entire decade (e.g., 1940 = 1940–1949). The first graph in the upper left shows the timing of imagery for all G&PS in the American West, and the remaining graphs show the timing for each state.**

The aerial photography for all inventories, including the 24K, was acquired within a similar time window, with differences of no more than 10 years. As mentioned previously, this mapping period coincided with a period of little glacier change, and we suggest that any area differences between the inventories and the 24K are probably the result of differences in interpretation rather than actual area differences. Generally speaking, the identification of a G&PS (versus seasonal snow) and the interpretation of its outline can differ between cartographers and glaciologists because of personal expertise, image quality, and extent of seasonal snow. Indeed, differences between glaciologists alone can be significant (DeVisser and Fountain, 2015).

Although one might expect that comparison of inventories would be simple, differences in approach and interpretation confound comparisons in terms of both number of features and areas estimated. For example, Post et al. (1971) and Spicer (1986) grouped small neighboring glaciers within the same identification code rather than treating them as individual features as in the 24K. In some cases, a flow divide was not included, and the entire ice mass, such as capping a volcano, was identified as a single glacier; in other cases two connected glaciers were divided but the specific location of the flow divide was unknown. In no case could we compare the glacial outlines between inventories because the regional inventories published fixed-scale paper maps showing glacier location with the shape and size represented emblematically. Three specific differences between the 24K and regional inventories include image rectification, scale, and feature inclusion. The 24K inventory is based on rectified, vertical, aerial photography from which paper maps were made, whereas the regional is based on unrectified vertical and oblique aerial photography from which the outlines were drawn on pre-existing topographic paper maps. The two sets of inventories were produced at different scales with the 24K at 1:24,000 and the regional at 1:62,500. Finally, the 24K inventory identifies G&PS whereas the regional attempts to identify only glaciers.

Because of the methodological differences between inventories, they need to be reconciled before they can be quantitatively compared. The regional inventories have already been published in paper form, therefore it was easier to adjust the preliminary digital 24K inventory. For the Olympic Range, the 24K G&PS were grouped in the same manner for each small watershed to match Spicer's (1986) method. For the North Cascades, Post et al. (1971) stated they did not include "glaciers" < 0.1 km^2, but a close examination of their report showed that 411 features were <0.1 km^2. These small features probably reflected a partial inventory of possible features <0.1 km^2, and because of this vagueness we eliminated all features smaller than this threshold from both Post et al (1971) and our 24K inventory. For the Sierra Nevada, Raub et al. (2006) included both "glaciers" and "ice patches" ≥ 0.005 km^2, and for our comparison, we used that area threshold to filter the 24K. Also, for total area we used the Raub et al. (2006) value for exposed ice rather than total area for the glacial features. The 24K essentially mapped only ice-exposed areas, ignoring the debris-covered ice.

The preliminary 24K and regional inventories were compared in two ways (Table 1). First, a direct "raw" comparison was made between inventories, with no adjustments. This comparison suffers, as mentioned, from different approaches in addition to different interpretations. The second method used the 24K adjusted to match each inventory's method of grouping and minimum size threshold. This comparison reflects the differences in G&PS identification and perimeter interpretation.

The number of G&PS identified by the raw 24K inventories exceeded the glaciological inventories in all re-

TABLE 1

Comparison of the cartographic and glaciological/regional inventories of glaciers and perennial snowfields (G&PS) for three different mountain ranges. The 24K refers to the preliminary cartographic inventory derived from the US Geological Survey 1:24,000 topographic maps. The Post, Spicer, and Raub inventories are the glaciological/regional inventories (Post et al., 1971; Spicer, 1986; Raub et al., 2006). Num refers to the number of G&PS, Max is maximum, Min is minimum. The rows within each mountain range are the original values from each inventory. The "Filtered" rows are the adjusted 24K data that replicate the inventory methods of the glaciological inventories. The adjusted Post data is explained in the text. The total area is rounded to the nearest 0.1 and the uncertainty of the 24K is 9%.

			Area				
Mountain Range	Inventory	Num	Total (km^2)	Max (km^2)	Min (km^2)	Mean (km^2)	Median (km^2)
North Cascades	24K	1935	288.4 ± 26.0	6.83	0.0004	0.15	0.03
	Post	756	275.6 ± 18.5	7.00	0.10	0.37	0.10
Filtered	24K	413	250.1 ± 22.5	6.83	0.10	0.61	0.22
≥0.1 km^2	Post	345	234.5 ± 14.4	7.00	0.20	0.71	0.30
Olympic	24K	391	37.3 ± 3.4	5.7	0.001	0.096	0.02
	Spicer	265	45.9 ± 0.3	6.1	0.01	0.17	0.05
Filtered	24K	257	36.5 ± 2.9	5.7	0.01	0.14	0.03
≥0.01 km^2	Spicer	265	45.9 ± 0.3	6.1	0.01	0.17	0.05
Sierra Nevada	24K	1719	39.15 ± 3.5	0.8	0.001	0.02	0.01
	Raub	1285	35.1	—	—	—	—
Filtered	24K	1313	37.86 ± 3.4	0.8	0.005	0.03	0.014
≥0.005 km^2	Raub	1285	35.1	—	—	—	—

gions between 134% and 256%. For total area, the 24K over-estimated the G&PS area in the North Cascades and Sierra Nevada by 105% and 112%, respectively, and underestimated the Olympics by 81%. Comparisons between the adjusted 24K and regional inventories were much better. The number of G&PS matched best for the Olympics and Sierra Nevada, 97% and 102%, respectively, and 120% for the North Cascades. The overestimate for the North Cascades is probably because of the inclusion of perennial snowfields in the 24K, whereas the regional inventory included only glaciers. For total area, the best results were found for the North Cascades and Sierra Nevada, both 107%, whereas for the Olympics, the results were 80%. The generally poor performance for the Olympics may be the result of poor aerial photography (quite snowy and of low contrast) used for the 24K, which made identification of G&PS perimeters difficult.

It is not surprising that the preliminary 24K inventory exceeds the regional in the number and area of G&PS. Although large glaciers with exposed ice and crevasses are easily identified, distinguishing seasonal snow from perennial snowfields using one-time photography is extremely difficult, if not impossible. This is particularly true for small (~0.1 km^2) features, and most likely the cartographers were more inclusive. Indeed, when snow and ice features were tracked over time in the Wind River Range, 37% (7.5% of the ice-covered area) of the 24K features were identified as seasonal (DeVisser and Fountain, 2015). Results also showed that the average size of these seasonal features was 0.02 km^2, yet perennial features were found to be as small as 0.003 km^2. The underestimates for the Olympics are unusual in our experience with 24K data in other regions (Dick, 2013; DeVisser and Fountain, 2015; Ohlschlager, 2015). In any case, the filtered 24K data provide a good estimate of G&PS, often within the uncertainty of total area for specific regions when the inventory methods are reconciled.

To better estimate the number of G&PS and reduce the number of seasonal snow patches from being included, we applied an area threshold. Unfortunately, the glaciological inventories provide little guidance; the region with the largest glacier cover (North Cascades) has a larger threshold, and the region with the smallest glacier cover (Sierra Nevada) has the smallest threshold. This difference is probably a matter of convenience based on the number of features encountered. Given this lack of clarity, we included all G&PS from the 24K inventory that are ≥0.01 km^2.

Inventory of Glaciers and Perennial Snowfields

The final inventory identified 5036 G&PS across eight states in 29 mountain ranges and totaled 671.5 km^2 (Fig. 2; Table 2). Only 373 are officially named by the U.S. Geological Survey. The most ice-covered state is Washington with 446.45 km^2 and 1931 G&PS. California has the second-largest population, but the total area is smaller than that of Wyoming. The mean G&PS area in California is almost half that of Wyoming. Perhaps the most unexpected outcome is finding G&PS in Idaho, which have not been reported and little studied. Overall, the G&PS ranged in area from 0.01 km^2 (the area threshold) to 10.59 km^2 (Emmons Glacier, Mount Rainier, Washington). The mean elevation of individual G&PS ranged from 596 m in the Cascade Range to 4394 m on top of Mount Rainier, both in Washington.

The exclusion of features smaller than 0.01 km^2, which are likely seasonal snow patches, does not affect the total ice-covered area significantly. With the snow patches included, the area is 690 km^2 and without, 672 km^2, or a 3% difference and smaller than the area of uncertainty of 9%. The difference in the number of G&PS is significant from a possible 8347 before applying the threshold to 5036 after, or a –40% change. A similar relationship between number and area was noted by Hagen et al. (1993) in Svalbard.

ANALYSIS

The G&PS are generally small, averaging 0.13 km^2, with a median of 0.03 km^2, and the population is skewed toward smaller ice masses (Fig. 3, part a). The largest 32 G&PS (0.6%) account for 25% of the total ice-covered area and the largest 132 (2.6%) for 50% of the area. Average elevations show a bimodal distribution peaking at 2500–2750 m and again at 3250–3500 m (Fig. 3, part b), which implies that the equilibrium line altitude, reflective of average elevation (Leonard and Fountain, 2003), is also bimodal. Most of the glacial area faces north-east to east, common to glacier populated regions in the northern hemisphere with mountain ranges oriented north-south and prevailing westerly winds (Fig. 3, part c) (Evans, 2006; Schiefer et al., 2008). The slope is normally distributed around the range of 30°–35°.

The mean elevations of G&PS have two geographic groupings. The Pacific Northwest, including northwest Montana, Oregon (not including the Wallowa), and Washington, has the most ice-cover area, and it is found largely below 3000 m (Fig. 4). In the rest of the American West, including the Sierra Nevada of California, Colorado, southern Montana, and Wyoming, most of the remaining G&PS are found above 3100 m.

Spatial Trends

From Washington State in the Pacific Northwest region, the average G&PS elevation rises southward and eastward (Fig. 5). From the Cascade Range,

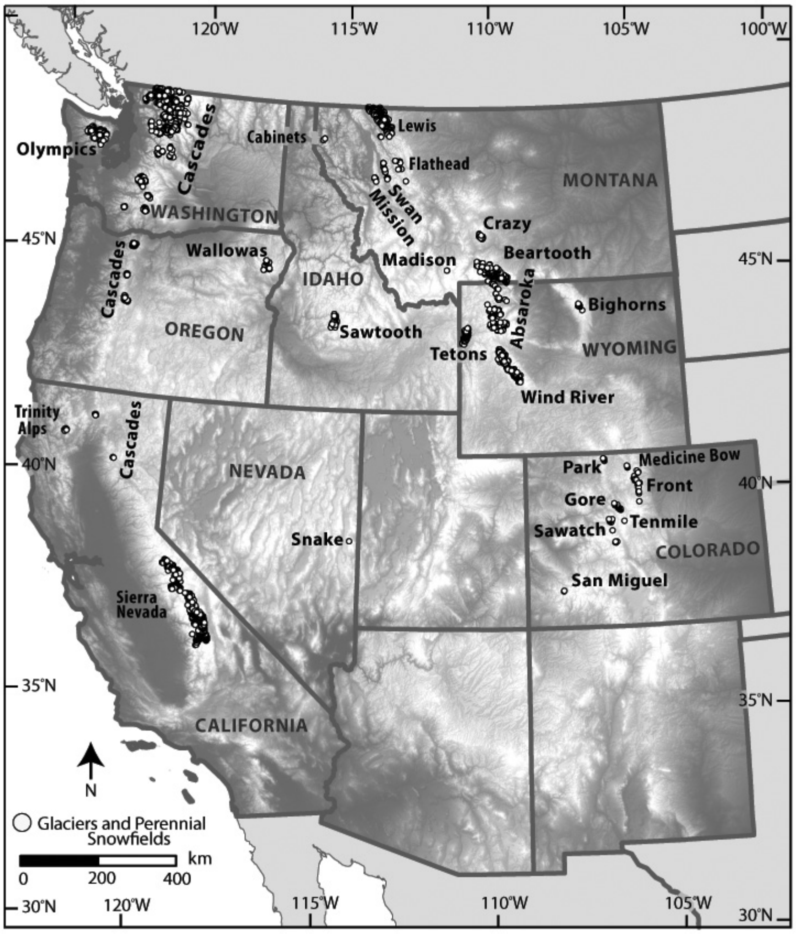

FIGURE 2. Distribution of G&PS in the American West (circles) with names of glacier-populated mountin ranges.

Washington, south to the Sierra Nevada, California, between longitudes 122°W and 119.7°W, the mean G&PS elevation rises at a rate of +1.3 m km^{-1} (r^2 = 0.86) as expected from the warmer climate and higher solar zenith to the south. Average summer air temperature, derived from the gridded climate data set, and averaged over the area of each G&PS, decreases to the south (–0.0018 °C km^{-1}; r^2 = 0.28) associated with the rising elevation of the glaciers. Average winter precipitation also decreases southward (–0.90 mm km^{-1}; r^2 = 0.47). These trends together are to be expected as less melt (caused by lower air temperatures) is balanced by less precipitation (proxy for snow accumulation). Gradients of elevation, air temperature, and precipitation were also examined for G&PS features larger than 0.05, 0.1, and then 0.5 km^2. In all cases the gradients changed little, although the correlation coefficient was smaller. Comparing the precipitation gradient to the temperature gradient provides a sense of the climatic environment favorable to G&PS. That is, when the air temperature increases by one degree, how much more snow is required to maintain the glacier (Leonard, 1989)? The ratio of the winter precipitation gradient to the summer air temperature gradient is +501 mm °C^{-1}.

For the inland north-to-south gradients (not shown), from the Lewis Range, Montana, to Wyoming and Colorado, G&PS elevation increased at a rate of +1.73 m km^{-1}, summer air temperature at –0.0026 °C km^{-1}, and winter precipitation at –1.36 mm km^{-1}. The ratio of the winter precipitation gradient to summer air temperature gradient is +521 mm °C^{-1}, with correlation coefficients similar to those in the Pacific Coast states. A west-to-east transect is also examined and is defined from the Olympic Mountains, Washington, to the Cascade Range, Washington, to the Lewis Range, Montana, between latitudes 47.4°N and 49°N (U.S. border with Canada). The glacier elevation increases eastward at a rate of +0.70 m km^{-1} (r^2 = 0.29), almost half of the north-south trend, summer air temperature shows no significant trend (–0.0005°C km^{-1}; r^2 = 0.01), and precipitation decreases at about the same rate as the north-south trend (–0.92 mm km^{-1}; r^2 = 0.11). The rate of change of precipitation per unit temperature change cannot be examined here due to the high variability in precipitation and overall poor correlation coefficients.

TABLE 2

Inventory of glaciers and perennial snowfields (G&PS) of the American West, derived from the U.S. Geological Survey 1:24,000 topographic maps. Max is maximum, and Min is minimum. Area uncertainty is ±9%.

		Elevation			Area		
State/Range	Number of G&PS	Max (m)	Min (m)	Mean (m)	Mean (km^2)	Median (km^2)	Total (km^2)
California	**925**	**4282**	**1890**	**3482**	**0.045**	**0.022**	**41.68**
Cascade	15	4266	2521	3173	0.336	0.035	5.04
Sierra Nevada	881	4282	2720	3524	0.039	0.022	34.76
Trinity Alps	29	2629	1890	2382	0.065	0.045	1.87
Colorado	**122**	**4287**	**3248**	**3685**	**0.038**	**0.027**	**4.66**
Front	46	4079	3292	3667	0.045	0.033	2.07
Gore	34	4010	3384	3705	0.043	0.026	1.48
Medicine Bow	5	3716	3462	3591	0.026	0.021	0.13
Park	16	3646	3248	3446	0.030	0.023	0.48
San Miguel	4	4236	3884	4086	0.046	0.036	0.18
Sawatch	16	4287	3620	3845	0.018	0.013	0.28
Tenmile-Mosquito	1	4003	3891	3949	0.032	—	0.03
Idaho	**69**	**3180**	**2548**	**2859**	**0.029**	**0.021**	**1.99**
Sawtooth	69	3180	2548	2859	0.029	0.021	1.99
Montana	**803**	**3784**	**1606**	**2659**	**0.083**	**0.034**	**66.69**
Beartooth-Absaroka	283	3784	2603	3248	0.075	0.036	21.17
Cabinet	4	2295	1807	2034	0.176	0.156	0.70
Crazy	44	3198	2658	2857	0.042	0.031	1.85
Lewis	405	3170	1606	2262	0.097	0.033	39.48
Madison	2	3332	3013	3153	0.021	—	0.04
Mission-Swan-Flathead	65	2819	2126	2459	0.053	0.035	3.45
Nevada	**1**	**3819**	**3405**	**3574**	**0.094**	**—**	**0.09**
Snake	1	3819	3405	3574	0.094	—	0.09
Oregon	**301**	**3415**	**1332**	**2290**	**0.138**	**0.028**	**41.56**
Cascade	259	3415	1332	2229	0.156	0.031	40.49
Wallowa	42	2849	2419	2666	0.026	0.021	1.07
Washington	**1925**	**4394**	**596**	**1959**	**0.231**	**0.041**	**444.75**
Cascade –Northern	1378	3284	596	1941	0.207	0.047	285.43
Cascade –Southern	294	4394	1069	2246	0.418	0.029	122.80
Olympic	253	2401	1081	1726	0.144	0.030	36.52
Wyoming	**884**	**4206**	**2694**	**3405**	**0.080**	**0.024**	**70.67**
Beartooth –Absaroka	225	3604	2852	3285	0.037	0.022	8.28
Bighorn	16	3730	3197	3414	0.060	0.045	0.97
Teton	159	4096	2694	3156	0.039	0.022	6.25
Wind River	484	4206	3114	3542	0.114	0.025	55.17
Total / Mean	**5030**	**4394**	**596**	**2680**	**0.134**	**0.030**	**672.09**

Climatic Environment

To examine the climatic environment of the G&PS, winter precipitation was plotted against mean summer air temperature and averaged over the extent of each G&PS using the PRISM data (Fig. 6, part a). Most of the summer air temperatures were found between 5 and 12 °C and winter precipitation

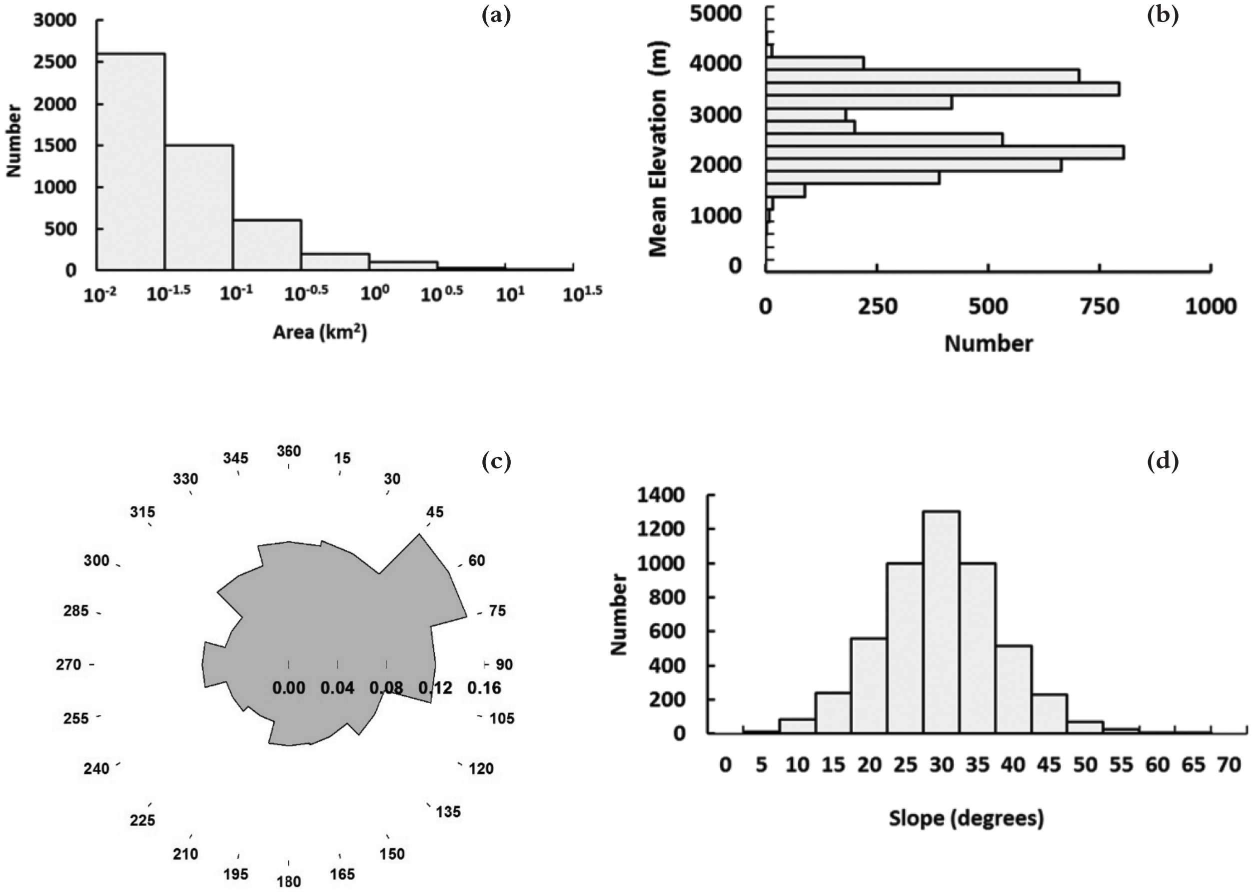

FIGURE 3. Topographic characteristics of G&PS in the American West. These figures present the distribution of feature population according to (a) area; (b) mean elevation; (c) mean aspect of area in 30 degree bins expressed as a fraction of total area; and (d) mean slope. In all plots the number is counted within each interval from those larger than the lower interval limit and up to and including the upper interval limit.

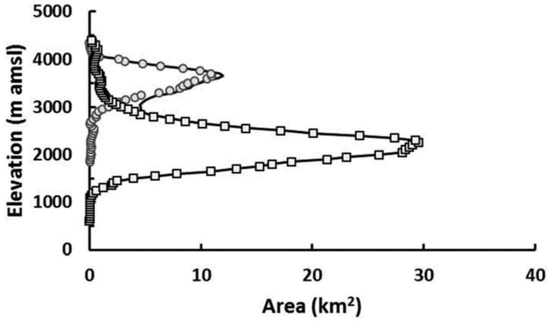

FIGURE 4. Total ice-covered area at 50 m intervals in the American West (solid line). The squares represent the ice cover for the Pacific Northwest region, which includes Oregon, Washington, and western Montana. The circles represent the ice-covered area for the Sierra Nevada of California, Beartooth Range of southern Montana, and the ranges in Wyoming and Colorado.

between 450 and 4000 mm. Large excursions toward colder temperatures represent the G&PS (>4000 m) on Mount Rainier and Mount Adams in the Cascade Range, and toward large precipitation (>4000 mm) represent G&PS in the Olympic Range and Mount Baker in the Cascade Range, all of which are in Washington State. Separating the data by region is more illustrative (Fig. 6, parts b and c). The G&PS climate of the Pacific Northwest is warmer (9 ± 2 °C; mean ± standard deviation) and wetter (2100 ± 630 mm) than the cooler (7 ± 1 °C), and drier (880 ± 330 mm) climate of the rest of the American West. The mean elevation of the G&PS in the Pacific Northwest is 2044 ± 340 m a.m.s.l., almost 1400 m lower than the rest of the American West at 3436 ± 259 m a.m.s.l. The remaining G&PS-populated mountain ranges (Trinity Alps, Mount Shasta, California; Sawtooth, Idaho; Madison Range, Montana; Wallowa Mountains, Oregon) shared characteristics of the two main regions.

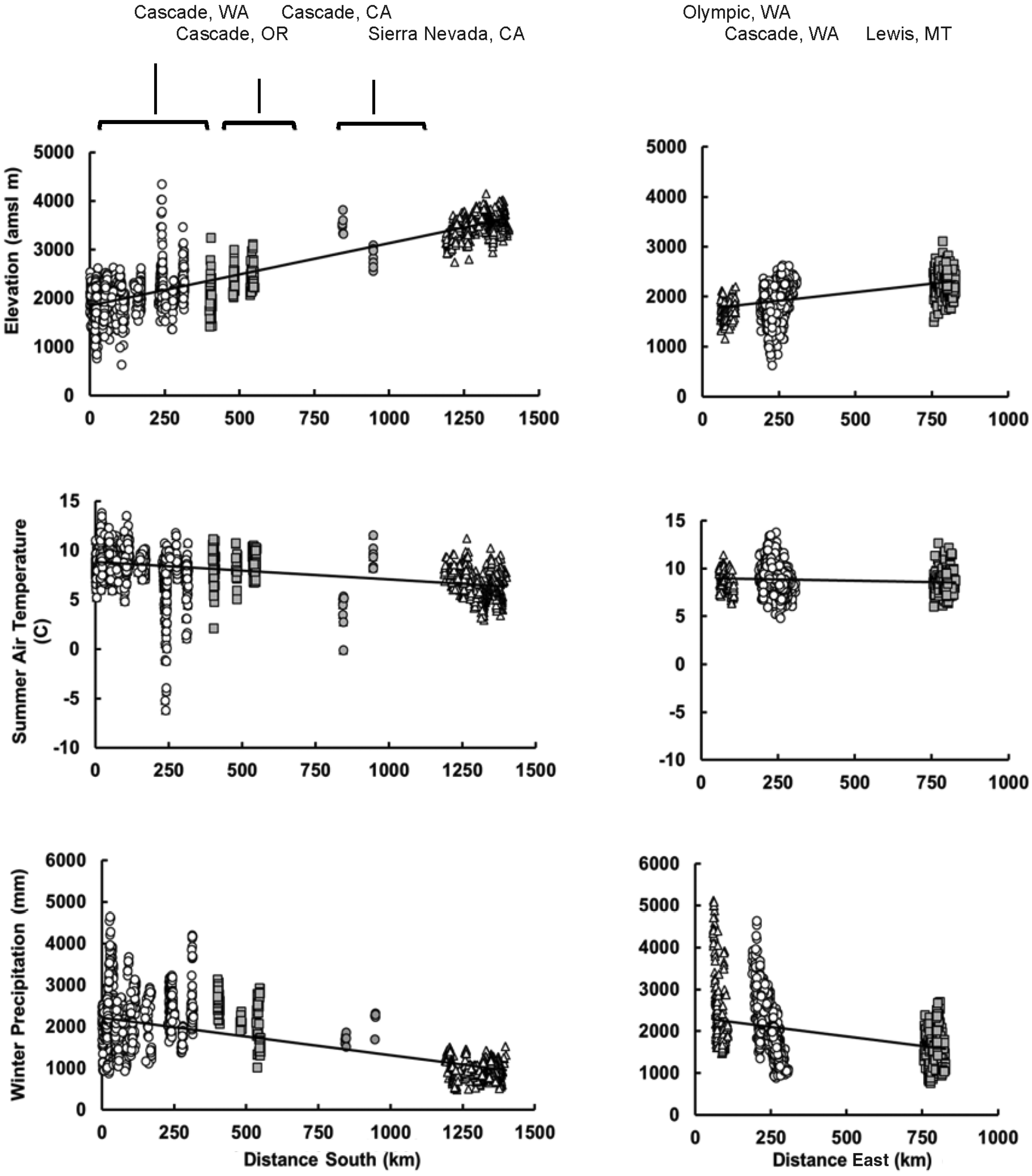

FIGURE 5. **Trends of elevation, summer air temperature, and winter precipitation for glaciers and perennial snowfields along two transects in the American West. Left column is a north-south transect in the western mountain ranges, and the right column is a west-to-east transect between 47°N and 49°N from Washington to Montana. Summer air temperature is the average for the months of June through September, and winter is the total precipitation from November through April, averaged over the period 1955–1990.**

Glaciers versus Perennial Seasonal Snowfields

An inventory of glaciers, as opposed to perennial snowfields, has important utility for assessing alpine erosion and predicting high volumes of sediment to streams. Therefore, knowing the distribution of glaciers is important for defining the pattern of glacial erosion and influence on stream water quality. By definition, a glacier is a perennial mass of ice or snow that moves (Cogley et al., 2011). To define movement from a suite of topographic measurements we estimated the basal shear stress, and if it exceeded the theoretical threshold yield stress of ice, 10^5 Pa (Cuffey and Paterson, 2010), the feature was considered to be a glacier. The basal shear stress is,

$$\tau_b = \rho g h \sin \alpha \qquad (1)$$

where ρ is ice density (900 kg m^{-3}), a value typical of glacial ice (Cuffey and Paterson, 2010), g is gravity (9.8 m

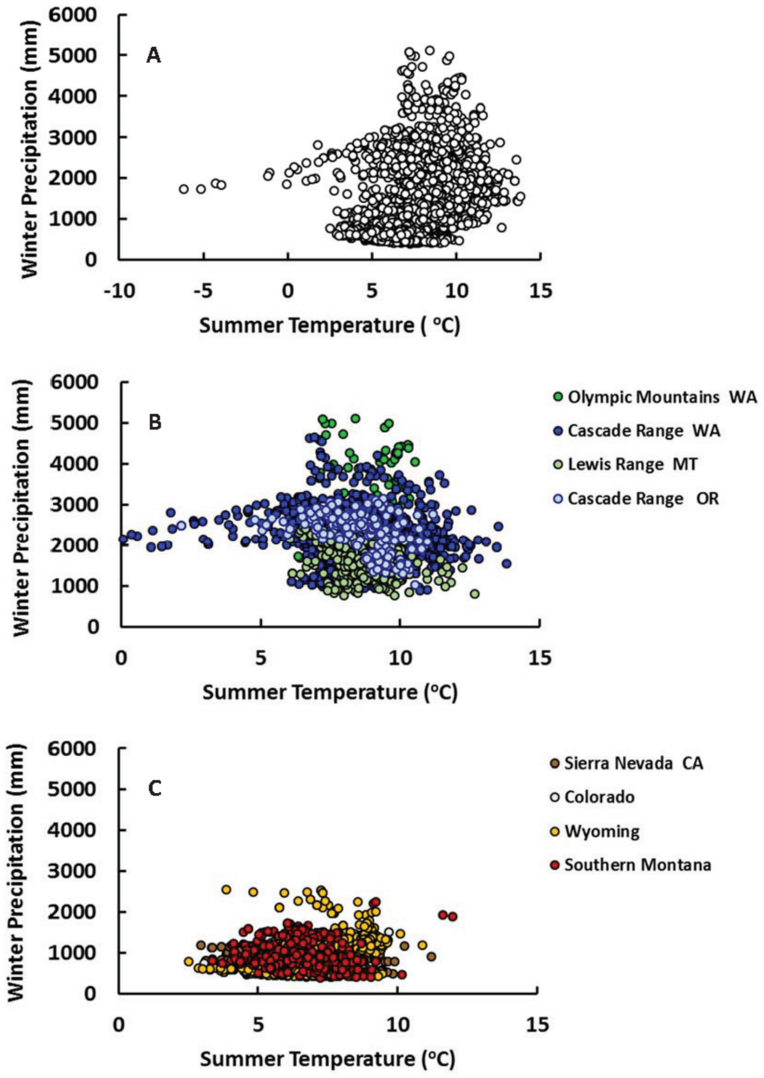

FIGURE 6. **Mean annual precipitation and mean annual air temperature for each G&PS, (a) for all glaciers and perennial snowfields; (b) for those in the Pacific Northwest, including Washington (Cascade Range, Olympic Mountains), Oregon (Cascade Range), and northwestern Montana (Lewis, Mission ranges); (c) California (Sierra Nevada), southern Montana (Absaroka, Beartooth, Crazy), Wyoming (Absaroka, Beartooth, Bighorn, Teton, Wind River), and Colorado (Front, Gore, Medicine Bow, Park, San Miguel, Sawatch).**

s^{-1}), *h* is ice thickness, and α is surface slope. Ice thickness was estimated from the area and volume of the G&PS, where area was taken from the 24K data, and volume was estimated from area-volume scaling relations of the form

$$V = \beta A^{\Upsilon}, \tag{2}$$

where A is the G&PS area, and β and Υ are parameters derived either theoretically or empirically (Chen and Ohmura, 1990; Farinotti et al., 2009; Bahr et al., 2015). Average thickness was estimated from Equation (2) by dividing both sides by area, yielding

$$\langle h \rangle = \beta A^{\Upsilon - 1}. \tag{3}$$

Equation (3) was substituted into Equation (1) to yield an estimate of basal shear stress as a function of G&PS area. To partly compensate for using an average value for *h*, the maximum slope, α, within the G&PS was used.

Equation (1), using the average thickness, was applied to the G&PS data summarized in Table 2 using the Chen and Ohmura (1990) values ($\beta = 21.346$; $\Upsilon = 1.145$), which were defined as the glacier subset "Cascades, small glaciers." In regional studies of glaciers in the western United States (Basagic and Fountain, 2011; Dick, 2013) these values best fit the estimated number and area of glaciers with the observed. Uncertainty in the volume estimate was unknown but for individual G&PS can be ±50%, but summed over a number of G&PS, it can be smaller because of compensating errors, ~20% (Granshaw and Fountain, 2006). We used the latter value as an estimate of volume uncertainty.

Results show that a total of 1276 glaciers (25% of the total G&PS), 554.2 km^2 (82%) in area, and 12.4 km^3 in volume populate the American West (Table 3). The dis-

TABLE 3

Estimated distribution and topographic characteristics of glaciers across the American West based the U.S. Geological Survey 1:24,000 topographic maps, using a shear stress threshold to distinguish glaciers from perennial snowfields. Num is number, Max is maximum, and Min is minimum. Area uncertainty is ±9%. Volume is estimated.

		Elevation			Area			Volume	
	Num	Max (m)	Min (m)	Mean (m)	Mean (km^2)	Median (km^2)	Total (km^2)	Mean (km^3)	Total (km^3)
California	**170**	**4266**	**2284**	**3580**	**0.14**	**0.08**	**23.11**	**0.002**	**0.401**
Cascade	6	4266	2998	3549	0.81	0.97	4.85	0.017	0.104
Sierra Nevada	157	4220	3084	3632	0.11	0.08	17.36	0.002	0.282
Trinity Alps	7	2629	2284	2447	0.13	0.09	0.90	0.002	0.015
Colorado	**17**	**4157**	**3440**	**3703**	**0.09**	**0.07**	**1.50**	**0.001**	**0.023**
Front	11	4046	3440	3675	0.09	0.07	0.94	0.001	0.015
Gore	4	3938	3598	3723	0.11	0.08	0.43	0.002	0.007
Medicine Bow	1	3716	3588	3633	0.04	—	0.04	0.001	0.001
San Miguel	1	4157	3884	4002	0.09	—	0.09	0.001	0.001
Idaho	**7**	**3075**	**2650**	**2882**	**0.07**	**0.08**	**0.52**	**0.001**	**0.008**
Sawtooth	7	3075	2650	2882	0.07	0.08	0.52	0.001	0.008
Montana	**242**	**3784**	**1674**	**2568**	**0.20**	**0.12**	**49.38**	**0.004**	**0.912**
Beartooth-Absaroka	69	3784	2803	3280	0.20	0.14	13.52	0.004	0.242
Cabinet	2	2295	1927	2131	0.25	—	0.50	0.004	0.009
Crazy	5	3139	2720	2933	0.12	0.13	0.58	0.002	0.009
Lewis	151	2989	1674	2245	0.22	0.11	32.97	0.004	0.622
Mission-Swan-Flathead	15	2819	2146	2487	0.12	0.10	1.81	0.002	0.030
Nevada	**1**	**3819**	**3405**	**3574**	**0.09**	**—**	**0.09**	**0.001**	**0.001**
Snake	1	3819	3405	3574	0.09	—	0.09	0.001	0.001
Oregon	**48**	**3415**	**1342**	**2392**	**0.67**	**0.38**	**31.71**	**0.015**	**0.689**
Cascade	48	3415	1342	2392	0.67	0.38	31.71	0.015	0.689
Washington	**635**	**4379**	**1069**	**2024**	**0.63**	**0.19**	**398.91**	**0.015**	**9.345**
Cascade -Northern	527	3284	1087	1994	0.48	0.17	254.82	0.011	5.681
Cascade -Southern	65	4379	1069	2447	1.77	0.75	115.03	0.046	2.990
Olympic	43	2401	1214	1751	0.68	0.34	29.06	0.016	0.674
Wyoming	**156**	**4206**	**2694**	**3459**	**0.30**	**0.12**	**47.24**	**0.006**	**0.991**
Beartooth-Absaroka	17	3563	3030	3299	0.14	0.13	2.34	0.002	0.037
Bighorn	5	3730	3290	3452	0.10	0.07	0.50	0.002	0.008
Teton Range	28	3723	2694	3143	0.11	0.09	3.11	0.002	0.050
Wind River	106	4206	3207	3568	0.39	0.13	41.29	0.008	0.896
Grand Total	**1276**	**4379**	**1069**	**2552**	**0.43**	**0.14**	**554.2**	**0.010**	**12.37**

tribution of glaciers across the states follows that of the G&PS population; Washington has the greatest number, 50% of total, 71% of the area, and 88% of the ice volume. Montana and Wyoming vie for second-most glacier population; although Montana has more glaciers (242 vs 156) and greater glacier-covered area (49.4 vs 47.2 km^2), Montana's ice volume is less (0.912 vs 0.991 km^3). The glaciers in Montana are smaller than those in Wyoming (average area 0.20 vs 0.30 km^2), and the non-linear nature of area-volume scaling (2) yields a larger volume for Montana. The number of G&PS officially named a "glacier" is 359, of which 314 were estimated to be glaciers. The glacier names are generally unique, although occasionally a small cluster of neighboring glaciers was identified with the same name, such as the Matthes Glaciers (9) in the Sierra Nevada. The most popular glacier name for different and individually identified glaciers is Grasshopper (4), of which three are in Montana and one is in Wyoming.

The number and distribution of perennial snow features was also calculated (Appendix Table A1) and yielded 3754, with a total area of 119 km^2 and a volume of 1.6 km^3. They represent 75% of the total number of G&PS, 19% of their total area, and 12% of their total volume. Most of the snowfields with the greatest area and volume are found in Washington, as expected. California had the second-most number of snowfields, with Wyoming coming close, but had a greater perennially snow-covered area and volume.

DISCUSSION

The basis of the 24K inventory is the 1:24,000-scale topographic maps from the USGS. This approach is similar to Schiefer et al. (2008), who abstracted glaciers from previously produced 1:20,000-scale base maps from the Terrain Resource Information Management program of British Columbia, Canada. The original USGS digital product contained numerous errors because of a faulty conversion from hard copy maps to digital outlines. Comparison of the corrected 24K inventory to three regional inventories compiled by glaciologists showed that, when adjusted for methodological differences, the 24K inventory compared well, and no glaciers were missing. However, it was clear from our own observations and from comparison with the regional inventories that seasonal snow patches were included, over-estimating the presence of G&PS.

Distinguishing seasonal snow patches from G&PS based on one-time photography is impossible. Only by tracking the features over a number of years can the seasonal or perennial nature of each feature be determined. Using an area threshold alone was an imperfect test because the size distribution and number of seasonal snow patches adopt a fractal dimension indistinguishable from that of small glaciers (Bahr and Meier, 2000). Indeed, glaciers smaller than seasonal snow patches have been identified (e.g., DeVisser and Fountain, 2015). Without the benefit of temporal data, however, we resorted to an area threshold filter. Based on comparison with regional glacier inventories, a threshold of 0.01 km^2 provided reasonable agreement. This threshold coincidentally matches that recommended by the World Glacier Inventory (Paul et al., 2010) and is smaller than other inventories (e.g., Western Canada, 0.05 km^2, Bolch et al., 2010; 0.1 km^2, Schiefer et al., 2008). We conjecture that the error in including a few seasonal snow patches that are larger than the area threshold compensates for the G&PS eliminated because they are smaller.

The total G&PS area of 672 km^2 is larger than 412 km^2 found by Selkowitz and Forster (2016). The difference is due to glacier recession over the ~40-year difference between inventories, mid-20th century for our inventory compared to 2010–2014 for Selkowitz and Forster (2016). However, what fraction of the difference is due to the vastly different methods is unclear. Our results may have over-estimated G&PS because of the presence of seasonal snow, and Selkowitz and Forster (2016) may have under-estimated the G&PS because of shadows and debris-covered ice that confounded the automated methods. Taken at face value, the area differences suggest a 39% loss in area. This loss is larger than that calculated by Selkowitz and Forster (2016) over the same period due to a difference in initial G&PS area. We used outlines from 1:24,000-scale maps, whereas Selkowitz and Forster (2016) used outlines from 1:100,000-scale maps, which included 6780 fewer snow and ice features than the 1:24,000 maps.

One surprising result was the population of G&PS in Idaho. The mountain ranges were glaciated during the last ice age, and rock glaciers are common (Butler, 1988; Hostetler and Clark, 1997; Thackray et al., 2004; Johnson et al., 2007). A review of the scientific literature revealed that Meier and Post (1962) identified six glaciers in the Sawtooth Range, close to our estimate of seven glaciers. The only published glacier study in Idaho was of a "glacier" on Borah Peak in the Lost River Range (Otto, 1977). Inspection of this feature using aerial photography shows that it is a highly debris-covered glacier with perhaps only its accumulation zone exposed. Although this debris-covered glacier is not included in our inventory of glaciers, it does highlight an important issue. The cartographers mapped what they believed to be perennial snow and ice and ignored any physical association with a larger debris-covered glacier or rock glacier. Therefore, some of our smaller G&PS might actually be a fraction of a larger glacial feature. Based on a cursory inspection, our size threshold has filtered most of these situations. However, we concede that this inventory is incomplete and excludes some debris-covered ice when adjacent and obvious glaciers are absent (e.g., Mount Rainier).

Of the 5036 G&PS identified in the American West, 1276 are glaciers covering an area of 554 km^2, or 83%

of the total perennial snow and ice covered area. When we compared our estimates of glacier population with those of Basagic and Fountain (2011) for the Sierra Nevada, California, and those of DeVisser and Fountain (2015) for the Wind River Range, Wyoming, we found that our estimates were larger. For the Sierra Nevada, we estimated 157 glaciers compared to 122, and for the Wind River Range we estimated 106 glaciers compared to 43. Identical parameters were used in area-volume scaling Equations (2) and (3) for the Sierra Nevada, but differences in GIS estimates of maximum slopes, which averaged 7°, caused 36 more G&PS to exceed the critical shear stress. For the glaciers in the Wind River Range the difference resulted from different parameters in the equations. These comparisons highlight the sensitivity of this glacier identification method to differences in slope and equation parameters; the estimated glacier population is suggestive rather than definitive.

For context, the glacier number and total area are similar to those in the Austrian Alps (1969 inventory), with 925 glaciers and a total area of 540 km^2 (Lambrecht and Kuhn, 2007) and smaller, by almost half, than those of Switzerland (1973 inventory; 2155 glaciers, 1307 km^2 area; Fischer et al., 2014). The mean size of the glaciers in the American West was 0.43 km^2, smaller than the mean for Austria, 0.58 km^2. The total volume of the glaciers was about 12.4 km^3.

The elevation distribution of the G&PS was bimodal—unlike, for example, the unimodal distribution in Austria and Switzerland (Lambrecht and Kuhn, 2007; Fischer et al., 2014)—and suggests different climatic regimes. This is a result of large climate differences in the American West compared to the smaller differences in the European Alps. The G&PS of the Pacific Northwest, including western Montana, Oregon, and Washington, are low elevation (mean 2044 m a.m.s.l.) and sometimes below tree line. They are maritime with warm summer temperatures (~9 °C) and high winter precipitation (~2100 mm). It is the heavy winter snowfall that allows the G&PS to reach such low elevations in spite of local annual air temperatures that are above freezing (Meier et al., 1971; Rasmussen et al., 2000). The high-elevation G&PS (mean 3426 m a.m.s.l.) found elsewhere in the American West, including Sierra Nevada of California; Beartooth Mountains of southern Montana; Wyoming; and Colorado, are continental with cooler summer temperatures (~7 °C) and drier winter precipitation (~880 mm). Although continental climates are typified by warmer summer air temperatures than maritime climates, the difference here is explained by the elevation difference of almost 1400 m. When the temperature is adjusted for elevation via the adiabatic lapse rate (potential temperature) the continental climate is indeed warmer.

Average G&PS elevations rise to the south and toward the east, consistent with the findings of Meier and Post (1962), because of gradients in summer air temperature and winter precipitation (Fig. 7). The highest minimum G&PS elevations are in Colorado. For the north-to-south transect from the Cascade Range, Washington, to the Sierra Nevada, California, the rate is 1.3 m km^{-1} and equivalent to the rate of 1.5 m km^{-1} of Meier and Post (1962), based on rough estimation from their Figure 3. The rate of increase eastward from the Olympic Mountains, Washington, to the Lewis Range, Montana, +0.70 m km^{-1}, is about half of the north-south gradient. It is also about half of the local east-west gradient across the North Cascade Range alone (Post et al., 1971; note that the distance scale in their Fig. 1 is incorrect), but twice the rate estimated from Meier and Post (1962). North of the Pacific Northwest, in British Columbia, Canada, a west-to-east increase in glacier elevation is also observed (Schiefer et al., 2007).

The ratio of precipitation to temperature at the glacier's equilibrium line elevation is a measure of the local environment that sustains the glacier (Leonard, 1989). For the G&PS in the American West the rate was +501 to 521 mm $°C^{-1}$ and was equivalent to that estimated at the equilibrium line for a number of glaciers (Leonard, 1989; Braithwaite and Zhang, 2000).

The low-elevation G&PS of the Pacific Northwest, particularly those in the Olympic Mountains and the Cascade Range of Washington and Oregon, are uniquely vulnerable to climate warming (Fig. 8). Winter air temperatures in this region are mild because of the moderating effect of the Pacific Ocean, and sea surface temperatures vary only a few degrees from an average of about 10 °C (Strub et al., 1987). Consequently, the low-elevation G&PS are increasingly subject to winter precipitation occurring as rain rather than snow as air temperatures approach 0 °C (Mote et al., 2005; Nolin and Daly, 2006; McCabe et al., 2007). Therefore, the G&PS receive less nourishment in winter and are exposed to an extended ablation season into autumn and spring (Rasmussen et al., 2000). But, like all the G&PS in the American West, they too will be subject to warming summer air temperatures.

CONCLUSIONS

The USGS 1:24,000-scale topographic maps provide a useful census of glaciers and perennial snowfields in the American West. The aerial photography on which the maps were based was collected over a 35-year period, 1950–1990, much of it during the mid-20th century

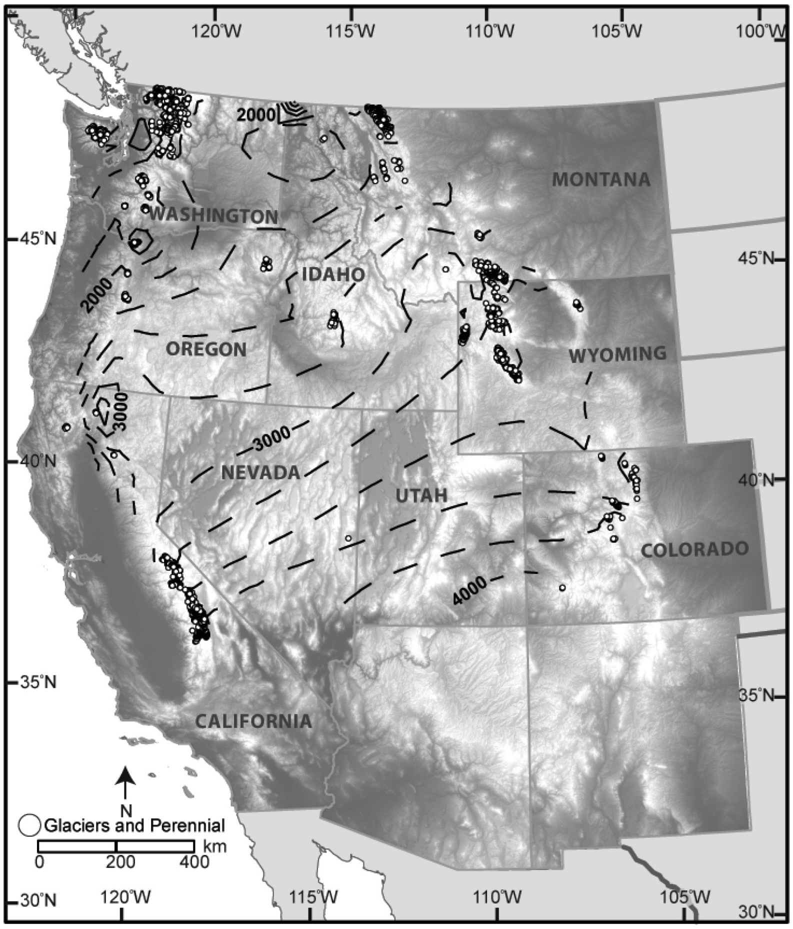

FIGURE 7. Contours (200 m) of mean elevation (m a.m.s.l.) of the G&PS across the American West.

cool period of glacier stability, thus making our inventory an excellent starting point for future inventories.

Comparison between the 24K inventory and regional glaciological-based inventories, conducted at about the same time, showed good agreement when differences in methods were reconciled.

The final inventory identified 5036 G&PS (672 km^2, 14 km^3) that populate eight western states, of which 1276 (554 km^2, 12 km^3) are considered glaciers. Elevation trends showed that the G&PS increase from the Pacific Northwest both southward and eastward, with the highest minimum elevations in Colorado. This trend is consistent with climatic trends of reduced precipitation southward and eastward and higher solar elevation southward. Comparing a recent inventory, the area of G&PS may have lost up to 39% of their area since the mid-20th century.

Generally speaking, two populations of G&PS are present in the American West. The smaller population in number and area has a continental climate characterized by colder winter temperatures, less winter precipitation, and higher elevations. These G&PS are found in the Sierra Nevada, California, southern Montana, Wyoming, and Colorado. The larger population is located in the maritime climate of Pacific Northwest and is characterized by warmer winter temperatures, high winter precipitation, and lower elevations. This second population of G&PS, especially those in the Olympic Mountains, are particularly vulnerable to climate warming because of their relatively warm winters and low elevations. Winter air temperatures are near 0 °C, and increased warming will change the phase of winter precipitation from snow to rain, thus reducing mass input to the G&PS, in addition to warmer air summer air temperatures and increased melt experienced by all G&PS.

The G&PS outlines generated by this study and provided to the National Snow and Ice Data Center, Boulder, Colorado, can be used as a template for locating such features in future studies and provide a datum against which future inventory results can be compared.

ACKNOWLEDGMENTS

This work was funded by the U.S. Geological Survey Western Mountain Initiative and the U.S. Forest Service.

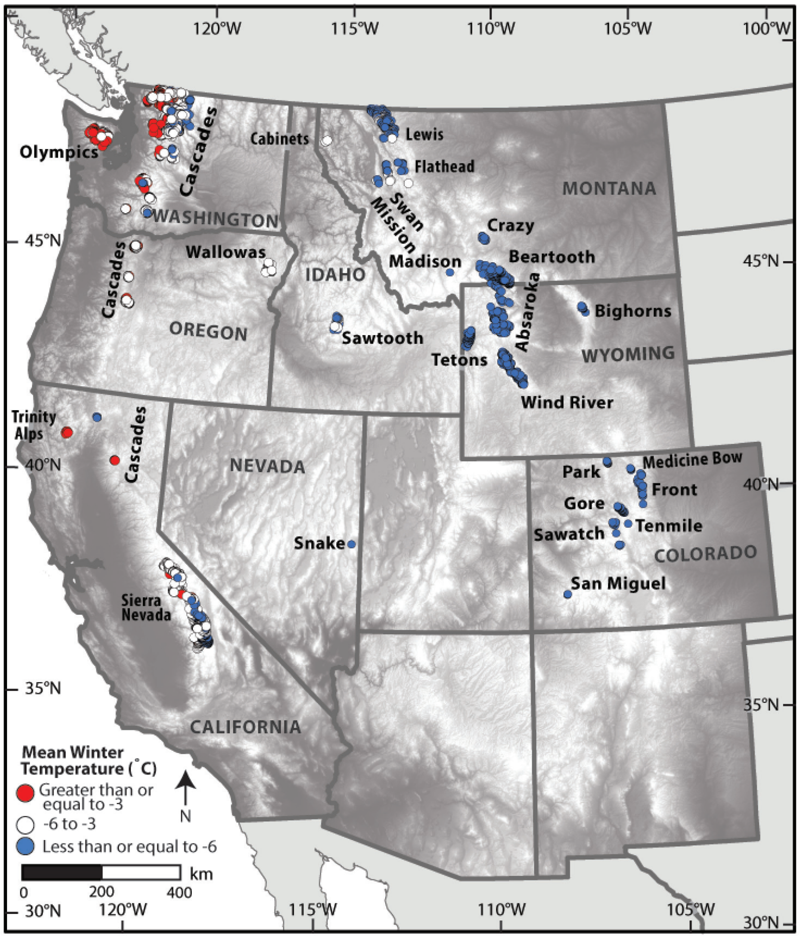

FIGURE 8. Map of winter (November–April) air temperatures at the locations of the G&PS based on PRISM data (Daly et al., 2007). The G&PS in red are the warmest (> –2 °C) and most vulnerable to future warming that would change the phase of precipitation from snow to rain. White circles are for G&PS with winter air temperatures –5 °C to –2 °C, and blue circles are for those < –5 °C.

We appreciate the efforts of Kristina Dick, Matt Hoffman, Keith Jackson, and Thomas Nylen in helping us form the original database.

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MS submitted 14 January 2017
MS accepted 22 May 2017

APPENDIX

TABLE A1

Estimated distribution and topographic characteristics of perennial snowfields across the western United States based on U.S. Geological Survey 1:24,000 topographic maps, using a shear stress threshold to distinguish glaciers from perennial snowfields. Max is maximum, Min is minimum, and Vol is estimated volume based on scaling relationships. Area uncertainty is ±9%.

		Elevation			Area			Vol
	Num	Max (m)	Min (m)	Mean (m)	Mean (km^2)	Median (km^2)	Total (km^2)	total (km^3)
California	**755**	**4282**	**1890**	**3460**	**0.025**	**0.019**	**18.57**	**0.239**
Cascade	9	3427	2521	2922	0.022	0.019	0.19	0.002
Sierra Nevada	724	4282	2720	3500	0.024	0.019	17.41	0.223
Trinity Alps	22	2629	1890	2362	0.044	0.038	0.97	0.014
Colorado	**105**	**4287**	**3248**	**3682**	**0.030**	**0.022**	**3.15**	**0.042**
Front	35	4079	3292	3665	0.032	0.028	1.13	0.015
Gore	30	4010	3384	3703	0.035	0.023	1.05	0.014
Medicine Bow	4	3697	3462	3580	0.023	0.018	0.09	0.001
Park	16	3646	3248	3446	0.030	0.023	0.48	0.006
San Miguel	3	4236	3959	4113	0.029	0.022	0.09	0.001
Sawatch	16	4287	3620	3845	0.018	0.013	0.28	0.003
Tenmile-Mosquito	1	4003	3891	3949	0.032	------	0.03	0.000
Idaho	**62**	**3180**	**2548**	**2856**	**0.024**	**0.019**	**1.47**	**0.019**
Sawtooth	62	3180	2548	2856	0.024	0.019	1.47	0.019
Montana	**561**	**3739**	**1606**	**2699**	**0.031**	**0.022**	**17.31**	**0.234**
Beartooth-Absaroka	214	3739	2603	3238	0.036	0.025	7.65	0.106
Cabinet	2	2071	1807	1938	0.101	------	0.20	0.003
Crazy	39	3198	2658	2847	0.032	0.026	1.27	0.017
Lewis	254	3170	1606	2273	0.026	0.020	6.51	0.085
Madison	2	3332	3013	3153	0.021	------	0.04	0.001
Mission-Swan-Flathead	50	2701	2126	2451	0.033	0.028	1.64	0.022
Oregon	**254**	**3148**	**1332**	**2271**	**0.039**	**0.024**	**9.85**	**0.140**
Cascade	212	3148	1332	2193	0.041	0.024	8.78	0.126
Wallowa	42	2849	2419	2666	0.026	0.021	1.07	0.014
Washington	**1290**	**4394**	**596**	**1928**	**0.036**	**0.025**	**45.84**	**0.634**
Cascade, Northern	851	2677	596	1908	0.036	0.026	30.61	0.422
Cascade, Southern	229	4394	1218	2189	0.034	0.021	7.77	0.108
Olympic	210	2243	1081	1721	0.036	0.023	7.46	0.104
Wyoming	**727**	**4096**	**2852**	**3393**	**0.031**	**0.020**	**22.85**	**0.316**
Beartooth-Absaroka	208	3604	2852	3285	0.029	0.021	5.94	0.079
Bighorn	11	3663	3197	3397	0.043	0.044	0.47	0.006
Teton	131	4096	2857	3159	0.024	0.019	3.13	0.040
Wind River	377	4029	3114	3534	0.035	0.020	13.30	0.191
Grand Total	**3754**	**4394**	**596**	**2723**	**0.032**	**0.022**	**119.04**	**1.624**