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Twentieth Century Glacier Change on Mount Adams, Washington, USA

Abstract

Mount Adams is a large glacier-clad stratovolcano located in southern Washington, USA. We examined the area change of the 12 glaciers on the mountain during the 20th century using historical topographic maps and aerial photographs. The total glacier area decreased by 49% (31.5 km^2 to 16.2 km^2) from 1904 to 2006. The glaciers showed a period of retreat during the first half of the century, followed by either a slowing of retreat or an advance from the 1960s to the 1990s. Subsequently, the glaciers resumed their rapid retreat. Glaciers on Mt. Adams show similar trends to those on both Mt. Hood and Mt. Rainier. The qualitative correlation between area change and trends in winter precipitation and summer temperature indicate a largely temperature-driven glacier shrinkage as the climate warmed since the Little Ice Age of the late 19th Century. No century-scale trends were noted in precipitation but decadal-scale variations in winter precipitation appear to enhance or buffer the effects of temperature on glacier change.

Introduction

Alpine glaciers are highly sensitive to changes in precipitation and temperature (Meier 1984, Paterson 1994), which make them good indicators of regional climate change. Because few climate records exist in alpine areas, the monitoring of glaciers can contribute to our understanding of climate change in these regions. Overall there has been a significant shrinkage of glaciers since the late 19th century, at the end of the Little Ice Age—roughly 1850 (Dyurgerov and Meier 2000, Oerlemans 2005). Locally, glacier meltwater contributes significantly to alpine runoff in late summer months which are typically the driest months of the year (Fountain and Tangborn 1985, Moore et al. 2009). The shrinkage of glaciers contributes 'extra' water through the mass wastage of the glacier. Globally, the shrinking of alpine glaciers contributes significantly to sea level rise (Meier 1984, Kaser, et al. 2006).

The magnitude and rate of glacial recession and the timing of intervals of stagnation or advance varies between and within regions (Dyurgerov and Meier 2000). On Mt. Hood, Oregon, the areas of seven glaciers have decreased by an average of 34% from 1907 to 2004 (Jackson and Fountain 2007). The glaciers retreated from 1900 until the 1950s and then either retreated at a slower rate or advanced slightly until the 1970s, followed by further retreat to the present (Lillquist and Walker 2006, Jackson and Fountain 2007). Glaciers on Mount Rainier, Washington decreased by 22% between 1913 and 1994 (Nylen 2004). In the North Cascades National Park complex, Washington, total glacier area decreased 7% from 117.3 ± 1.1 km^2 in 1958 to 109.1 ± 1.1 km^2 in 1998 (Granshaw and Fountain 2006).

Elsewhere in the American West glacier shrinkage has been more dramatic. The glaciers in the Sierra Nevada, California, show an overall area loss of 56% from 1900 to 2004 (Basagic 2008). In the northern Rocky Mountains, glaciers in Glacier National Park show varying degrees of retreat. Among the glaciers, Agassiz and Jackson exhibited a 70% area loss from the 1850s to 1979, while Sperry lost 74% and Grinnell lost 59% (Key et al. 2002). Most of the glaciers show a slowing in the rate of retreat from the 1940s to the 1970s, which then increased again to the 1990s (Key et al. 2002). In the southern Rocky Mountains the glaciers in Rocky Mountain National Park, Colorado, decreased in area by about 40% during the first half of the 20th century, grew slightly from the mid-1940s to the end of the century, and have retreated more rapidly since (Hoffman et al. 2007).

The extent of glaciers of Mount Adams and their change with time have not been reported. Here, we examine the glacier change on Mt. Adams from 1904 to 2006 and compare it to glacier change elsewhere and to variations in local climate.

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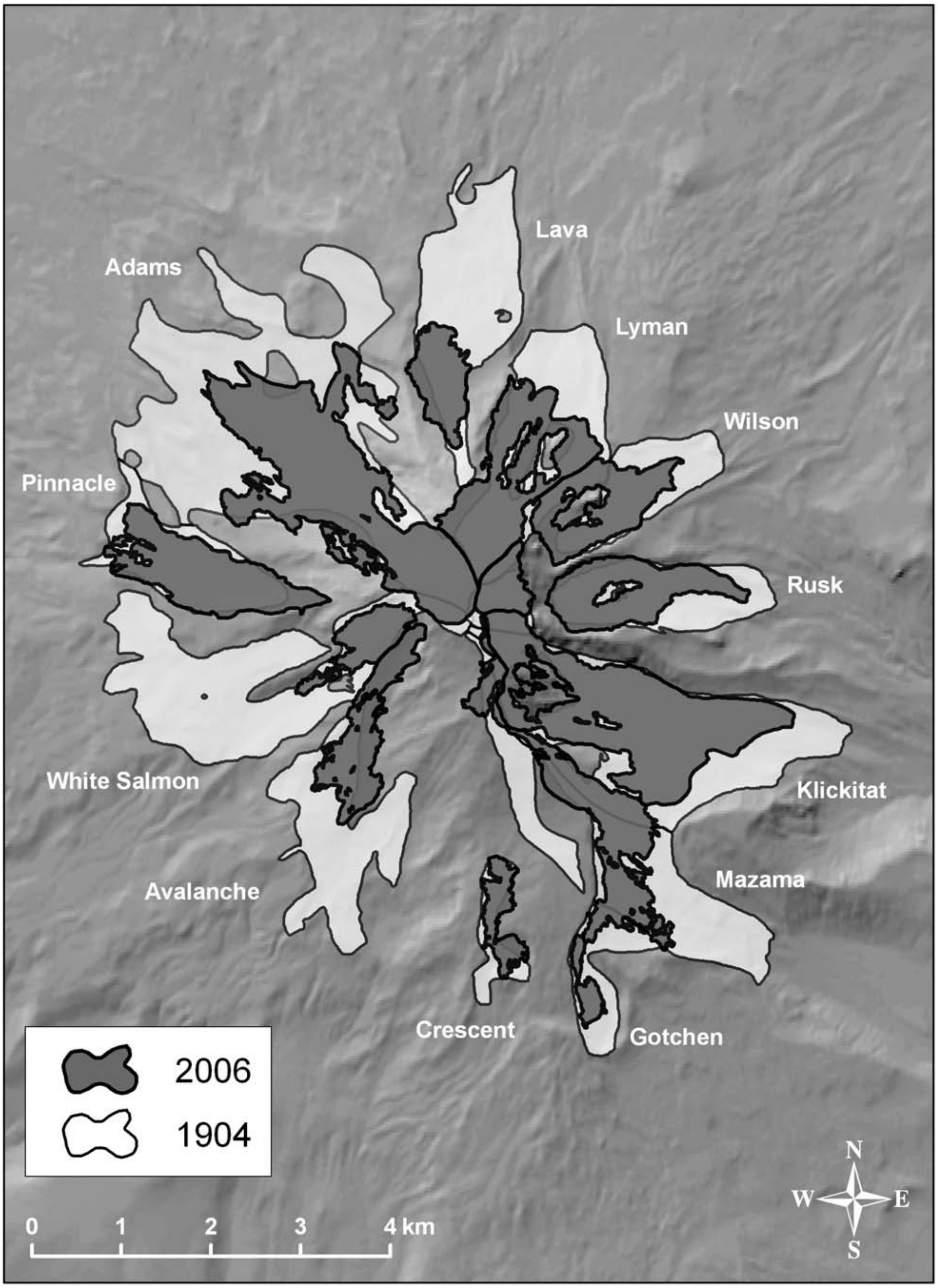

Figure 1. Glaciers of Mt. Adams, 2006 and 1904 outlines.

Study Area

Mount Adams rises to 3742m and is located in southern Washington (N 46.202621 W -121.490638). It is a stratovolcano similar to Mount Rainier and Mount Hood, all three of which are located in the Cascade Volcanic Arc of the Pacific geologic province. Mount Adams is mantled with 12 glaciers of varying sizes the surfaces of which may be partially covered with rock debris (Figure 1).

Methods

We examined changes in glacier area on Mt. Adams using a variety of data sources (Table 1). For the entire mountain we examined a U.S. Geological Survey 1:125,000-scale topographic map for 1904, 1:24,000 for 1969, and digital orthographic aerial photographs (DOQ) for 1998 and 2006. We derived additional areas for Lyman Glacier from aerial photographs for 1958, 1981, and 2000. Oblique aerial photographs acquired from the Mazamas, a hiking club (Portland, OR), taken in 1936, were used to infer glacier area for Pinnacle, Adams, and White Salmon glaciers; as were photographs of Rusk Glacier taken in 1956.

The glacier perimeters were digitized directly from the maps into a geographic information system (ArcInfo 9.0 ESRI, Inc). The total uncertainty in glacier area results from positional uncertainty, digitizing uncertainty, and from interpretation. Positional uncertainty in the topographic maps is 12.2 m, a standard uncertainty defined by the U.S. Geological Survey (USGS). Map standards require that less than 10% of well-defined points have an error greater than 12.2 m (Fountain et al. 2007). This 12.2 m uncertainty was applied to the 1969 map, but doubled to 24.4 m for the 1904 map because it was created by plane-table methods prior to modern map standards. For the DOQs, glacier perimeters were defined by exposed glacial ice, firn, and snow. Rock debris that appeared to cover ice was also included in the glacier perimeter if signs of ice movement (crevasses) could be detected. For the 1998 and 2006 DOQs the positional uncertainty is the root mean square error (RMSE) found in the metadata of the image. The 1936 and 1956 ground-based photographs were compared to the maps and DOQs to pick out landmarks to best estimate glacier extent. However due to the oblique camera perspective, uncertainty could not be calculated. The ground-based photographs were used to show the trend in area between 1904 and 1969 and not used to estimate area change.

TABLE 1. Summary table of data sources. Data types are topographic maps (TM), oblique aerial photos (OP), vertical aerial photos (AP) and digital orthographic photographs (DOQ). Data sources are, Mazamas, a hiking club in Portland, Oregon; the Department of Agriculture, National Agricultural Imagery Program (NAIP); US Geological Survey (USGS); and the US Forest Service (USFS) offices in Vancouver, WA and Portland, OR.

Year	Data Type	Source	Glaciers
1904	TM	US Geological Survey	All
1936	OP	Mazamas www.mazamas.org	Adams, WhiteSalmon, Pinnacle
1956	OP	Mazamas www.mazamas.org	Rusk
1958	AP	USFS	Lyman
1969	TM	US Geological Survey	All
1981	AP	USFS	Lyman
1998	DOQ	US Geological Survey www.earthexplorer.usgs.gov	All
2000	AP	USFS	Lyman
2006	DOQ	NAIP www.atterbury.com/store/Imagery	All

The glaciers were digitized with approximately a 1:5000 magnification to maximize the accuracy and efficiency and maintain good image resolution. The accuracy of the digitization was assessed by zooming to 1:1000, and measuring the distance between the digitized perimeter and the actual glacier perimeter on the map or photo at several points around the glacier. The absolute difference between the points and the actual edge were then averaged and the resulting value used for the digitizing uncertainty.

Interpretation uncertainty is the uncertainty in the location of the glacier perimeter based on our examination of the photographs. This uncertainty is caused by seasonal snow cover, rock-debris, or shadows. In situations where we are unable to discriminate the glacier boundary with certainty, we digitize two perimeters, one excluding the area in question and one that includes it. The resulting interpretation uncertainty is the difference between the maximum and minimum extents and the average of the two.

The total uncertainty is the square root of sum of the squared uncertainties for position, digitizing, and interpretation. When present, the interpretation uncertainty is typically much larger than the other two. The total uncertainty is applied to the glacier perimeter as an inner and outer buffer zone, each equal in magnitude to the uncertainty, such that the total width of the zone is twice the uncertainty (Granshaw and Fountain 2006). The final uncertainty for the glacier area is one-half of the difference in area between that defined by the inner buffer and the outer buffer. This method assumes correlation among all vertices, yielding a conservative (large) uncertainty (Hoffman et al. 2007). Because of scale effects, a 12 m positional uncertainty results in less than 5% uncertainty in area for glaciers larger than ~0.75 km^2. Since all but two of the glaciers on Mt. Adams are at least 1 km^2, the conservative nature of the buffer method does not restrict our ability to detect area change for these glaciers.

Climate Trends

To investigate glacier response to climatic variations we correlated summer air temperature and winter precipitation with changes in glacier area. Summer temperatures are commonly used as an index of glacier mass loss through melt and winter precipitation is an index of mass accumulation of snow (Tangborn 1980, Paterson 1994). No long-term climate data stations could be found close to Mount Adams, therefore we employed data from the gridded climate model, Parameter-elevation Regressions on Independent Slopes Model (PRISM) that uses point measurements of climate data and a digital elevation model (DEM) to interpolate the climate over unmeasured regions (Daly et al. 2008). To check the PRISM data estimated for Mount Adams, we compared the precipitation and temperature data from PRISM to the closest climate station at the Mount Adams Ranger station (1949-2006) located 22 km south of Mount Adams (USFS-MAR). The PRISM data from the 4 km x 4 km cell centered over the summit of Mount Adams was found to correlate well with the ranger station. Summer (July–September) mean air temperature and total winter (December– February) precipitation from monthly PRISM data (1900-2006), were correlated with glacier area changes. We applied a five-year running mean to the seasonal temperature and precipitation data.

Results

We used the USGS topographic map, derived from aerial photographs acquired in 1969, as the baseline for our study because it supplies both glacier perimeters and topographic data. Our data before and after this map include only area. The 12 glaciers on Mt. Adams in 1969 range in mean elevation from 2348m (Gotchen Glacier) to 2922 m (Lyman Glacier). The total glacier cover at that time was 21.73 ± 0.99 km^2; Adams Glacier is the largest glacier, 6.93 ± 0.59 km^2, and Gotchen Glacier the smallest, 0.78 ± 0.14 km^2 (Table 2). Like other stratovolcanoes there is no preferred aspect for glacier occurrence.

TABLE 2. Glacier areas for 1904, 1969, 1998, and 2006, ordered largest to smallest according to the 1904 areas. Total Loss is from 1904 to 2006. W. Salmon is the West Salmon Glacier. Fractional (Fract), Elevation (Elev) and aspect (Asp) are based on the glacier topography in 1998.

Glacier	**1904** km^2	**1969** km^2	**1998** km^2	**2006** km^2	**Total Loss** km^2	**Fract Loss** %	**Elev Range** m	**Mean Elev** m	**Asp**
Adams	6.93 ± 0.59	5.16 ± 0.61	4.52 ± 0.41	3.68 ± 0.31	3.25 ±0.67	-47	2140-3745	2711	NW
Klickitat	5.37 ± 0.42	2.84 ± 0.26	3.14 ± 0.14	2.93 ± 0.18	2.44 ±0.46	-46	2203-3740	2788	SE
W. Salmon	3.56 ± 0.42	1.21 ± 0.24	1.40 ± 0.09	0.51 ± 0.04	3.05 ±0.42	-86	2202-3544	2791	SW
Lava	2.62 ± 0.27	1.65 ± 0.18	1.51 ± 0.12	0.67 ± 0.09	1.95 ±0.28	-74	2203-3077	2484	N
Mazama	2.62 ± 0.40	2.00 ± 0.30	1.90 ± 0.10	1.40 ± 0.10	1.21 ±0.41	-46	2340-3483	2662	SE
Lyman	2.45 ± 0.29	1.56 ± 0.24	1.49 ± 0.11	1.62 ± 0.10	0.83 ±0.31	-34	2225-3709	2922	NE
Avalanche	2.09 ± 0.30	2.07 ± 0.25	1.35 ± 0.13	0.86 ± 0.06	1.23 ±0.31	-59	2202-3544	2791	SW
Rusk	1.91 ± 0.24	1.50 ± 0.15	1.70 ± 0.09	1.47 ± 0.14	0.44 ±0.28	-23	2217-3190	2701	E
Pinnacle	1.51 ± 0.18	1.56 ± 0.42	1.72 ± 0.28	1.41 ± 0.11	0.10 ±0.21	-7	2109-3222	2401	W
Wilson	1.20 ± 0.14	1.44 ± 0.15	1.43 ± 0.06	1.03 ± 0.11	0.17 ±0.18	-14	2251-3239	2640	NE
Gotchen	0.78 ± 0.14	0.33 ± 0.11	0.36 ± 0.04	0.17 ± 0.02	0.62 ±0.14	-78	2208-2553	2348	SE
Crescent	0.47 ± 0.12	0.41 ± 0.11	0.58 ± 0.05	0.44 ± 0.07	0.03 ±0.14	-6	2291-2822	2589	S
TOTAL	31.51±1.12	21.73 ±0.99	21.1 ± 0.59	16.18 ±0.19	15.33±1.14	-49			

TABLE 3. Area for Lyman Glacier.

Year	Area (km^2)
1904	2.45 ± 0.29
1958	1.71 ± 0.11
1969	1.56 ± 0.24
1981	1.47 ± 0.17
1998	1.49 ± 0.11
2000	1.58 ± 0.17
2006	1.62 ± 0.06

Glacier areas were calculated for 1904, 1969, 1998 and 2006, for all 12 glaciers on Mount Adams (Table 2). The more detailed history of Lyman Glacier is summarized in Table 3 and the changes in all glaciers are depicted in Figure 2. The RSME for the uncertainty was 1.8m for the 1998 image and 3m for the 2006 image. For the DOQs for Lyman Glacier, 1958, 1981 and 2000, the RSME was 7m, the USFS standard for DOQs (USGS, 1992). The sum of the position and digitizing uncertainties, yielded buffer distances of 26.4 m for 1904 and 15.8 m for 1969 maps, and 6.3 m for the 1998 and 4.2 m for the 2006 aerial images. The 1936 areas for Pinnacle, Adams and White Salmon glaciers and the 1956 area for Rusk Glacier are not included in Table 2 because the area is based on oblique photos (Figure 2). The error bars for these cases extend from the top of the 1904 error bar to the bottom of the 1969 error bar to denote large uncertainty.

Overall, the total area of the 12 glaciers decreased by 15.33 ± 1.14 km^2 (49%) from 1904 to 2006. White Salmon Glacier lost the most fractional area (86%) whereas Crescent Glacier lost the least (6%). All glaciers retreated from 1904 to 1969, but they either slowed the rate of decrease or advanced from 1969 to 1998. Between 1904 and 1969 the smaller glaciers (< 2km^2) averaged 14% area loss, compared to the larger glaciers that averaged 34%. All glaciers, except Lyman, decreased in area from 1998 to 2006. Lyman Glacier shows a small increase in area from 1998

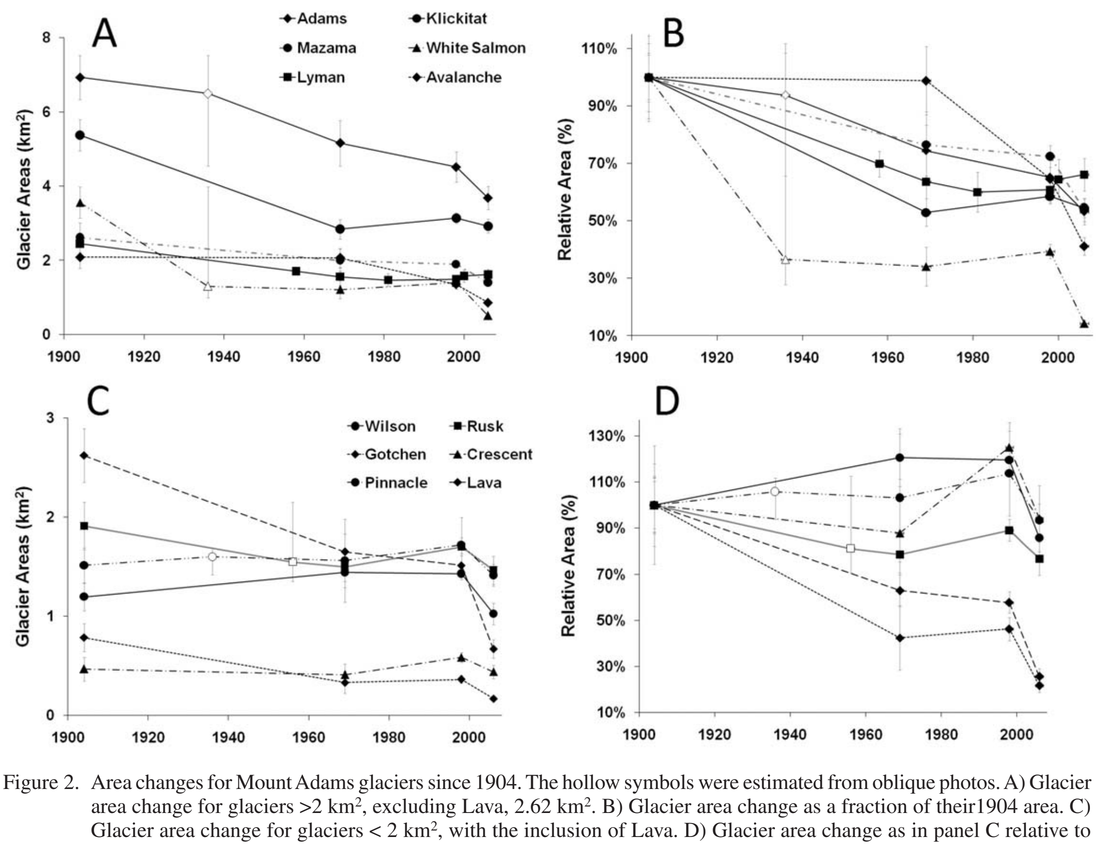

Figure 2. Area changes for Mount Adams glaciers since 1904. The hollow symbols were estimated from oblique photos. A) Glacier area change for glaciers >2 km^2, excluding Lava, 2.62 km^2. B) Glacier area change as a fraction of their1904 area. C) Glacier area change for glaciers < 2 km^2, with the inclusion of Lava. D) Glacier area change as in panel C relative to 1904.

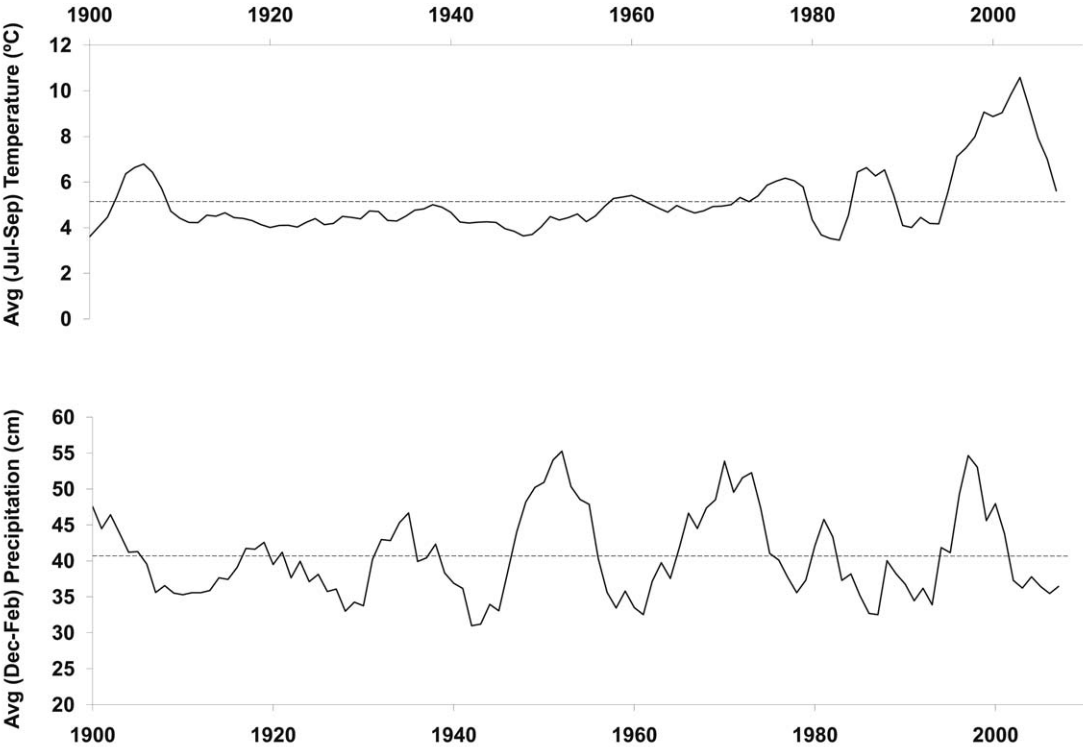

Figure 3. The top graph shows average summer (Jul-Sep) temperature over the past 106 years, as a 5-year running average. The bottom graph shows the average winter (Dec-Feb) precipitation as a 5-year running average. Horizontal lines indicate the overall temperature and precipitation means. The dotted lines show the 1900-2008 averages.

to 2006 that is also within the uncertainty of our measurements (Figure 2).

To understand the causes for the glacier variation over the past century, we examined the variation in local climate using summer air temperature as a proxy for snow and ice melt (glacier mass loss) and winter precipitation (glacier mass increase). Summer air temperatures and winter precipitation from 1900 to 2006 showed significant variations (Figure 3). The summer air temperature was fairly constant over the first 50 years except for a transient warming of almost 3 °C during the first decade. Since about 1950 air temperatures began to increase, with a sharp rise in the 1990s until the early 2000s when the temperature began a sharp decrease to the present. However, the 50-year warming period is punctuated by two cold periods, each lasting about 5 years. Overall, the summer air temperature of the recent 50 years is about 1.5 °C warmer than the first 50 years. For winter precipitation no overall trend is evident; instead, the record is characterized by a 10-15 year wet/dry cycle. The three wettest periods are found at 1950, 1970, and 2000, with the driest periods at about the early 1940s, 1960, and the late 1980s. The average winter precipitation over the century has stayed fairly constant.

We compared the total ice-covered area on Mount Adams at 1904, 1969, 1998 and 2006 to summer air temperature and winter precipitation. Each data set was normalized by subtracting the mean from each data point and dividing by the standard deviation, which were then plotted (Figure 4). The glacier retreat from 1904 to 1969 coincides with a period of generally colder than average summer temperature over the 20th century and generally below average precipitation. However, it appears that pre-1900 air temperatures were much colder, coinciding with the Little Ice Age (Moore et al. 2009) and the temperatures in the 20th century are warmer resulting in significant glacier shrinkage. For the period of 1969 to 1998 the summer air temperatures appear to be out of phase with winter precipitation such that during cool phases

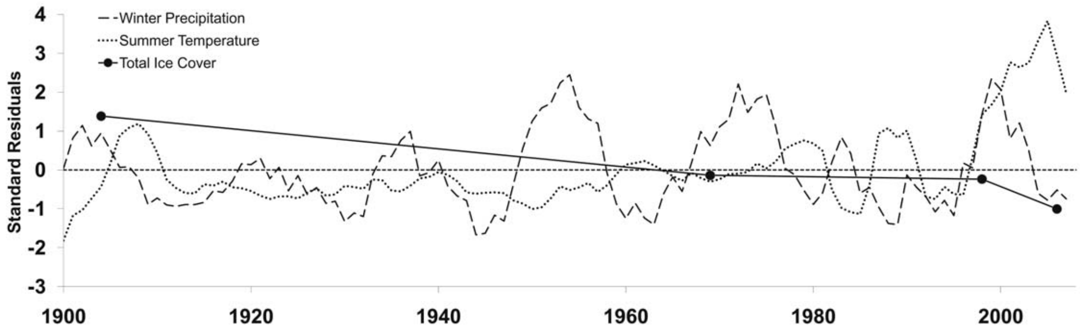

Figure 4. Comparison of winter (Dec-Feb) precipitation, summer (Jul-Sep) temperature, and total glacier cover on Mount Adams.

winter precipitation was high. During the early part of this period cool summer temperatures and high winter precipitation probably buffered the opposite phase in the latter part resulting in little or no glacier change. Since 1998 dramatically warm summer temperatures have dominated the compensating effects of winter precipitation and the glaciers have shrunk drastically.

Discussion

Compared to Mount Rainier and Mount Hood (located about 70 km north and 80 km south of Mount Adams, respectively), the magnitude and rates of glacier change on Mount Adams are similar. Total glacier coverage on Mount Rainier decreased by 24% (109.86 km^2 to 83.47 km^2) between 1913 and 2002 at a rate of about 0.3 km^2 yr^{-1} (Nylen 2004). On Mount Hood, total glacier coverage decreased by 32% (10.01 km^2 to 6.79 km^2) between 1907 and 2004 at about 0.03 km^2 yr^{-1} (Jackson and Fountain 2007). The rates of change for both mountains are similar if scaled by initial total glacier area. On Mount Adams, total glacier area decreased by 49% (31.51 km^2 to 16.18 km^2) from 1904 to 2006 at about 0.15 km^2 yr^{-1}. This fractional retreat is much greater than that for either Mount Rainier or Mount Hood. Of the three mountains, Mount Rainier is the highest peak, furthest north, and has the greatest ice cover, followed by Mount Adams and then Mount Hood. Topographic differences and latitude largely explain the differences in glacier cover; higher peaks collect more snow and melt less, compared to those at lower and more southerly elevations. Why the glaciers on Mount Adams have retreated more than those at Mount Hood is unclear. Mount Adams is the eastern-most of the three volcanoes and somewhat in the rain shadow of the Cascades. This difference, in some way, may be a contributing factor to the enhanced glacier loss.

The temporal pattern of glacier change on Mount Adams follows a pattern of advance and retreat similar to those on Mount Hood (Lillquist and Walker 2006, Jackson and Fountain 2007) and on Mount Rainier (Nylen 2004). Glaciers on Hood and Rainier also show a period of rapid retreat in the early 1900s, followed by a period of either advance or slowing in the rate of retreat up to about the early 1970s, followed by another period of retreat that became more rapid in the mid 1990s. Glaciers on Mount Adams show a period of retreat during the first half of the century, followed by a period of little change or advance, and then another period of rapid retreat in the latter part of the century. This temporal pattern of glacier change compare well to changes in summer air temperature and winter precipitation, consistent with results from Mount Hood and Mount. Rainier (Nylen 2004, Lilliquist and Walker 2006, Jackson and Fountain 2007).

The main driver of glacier recession appears to be summer air temperature, as little change in precipitation has occurred over the past century. All three temperature data sets show a significant increase in summer temperature beginning around the 1980s (e.g., Nylen 2004, Lilliquist and Walker 2006) corresponding to the rapid retreat in glacier area during the latter part of the 20th century for several studies. This is noted also in Colorado (Hoffman et al. 2007) and in Montana (Key et al 2002).

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