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# Whole-edifice ice volume change A.D. 1970 to 2007/2008 at Mount Rainier, Washington, based on LiDAR surveying

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## ABSTRACT

**Net changes in thickness and volume of glacial ice and perennial snow at Mount Rainier, Washington State, have been mapped over the entire edifice by differencing between a high-resolution LiDAR (light detection and ranging) topographic survey of September–October 2007/2008 and the 10 m lateral resolution U.S. Geological Survey digital elevation model derived from September 1970 aerial photography. Excepting the large Emmons and Winthrop Glaciers, all of Mount Rainier's glaciers thinned and retreated in their terminal regions, with substantial thinning mainly at elevations <2000 m and the greatest thinning on south-facing glaciers. Mount Rainier's glaciers and snowfields also lost volume over the interval, excepting the east-flank Fryingpan and Emmons Glaciers and minor near-summit snowfields; maximum volume losses were centered from ~1750 m (north flank) to ~2250 m (south flank) elevation. The greatest single volume loss was from the Carbon Glacier, despite its northward aspect, due to its sizeable area at <2000 m elevation. Overall, Mount Rainier lost ~14 vol% glacial ice and perennial snow over the 37 to 38 yr interval between surveys. Enhanced thinning of south-flank glaciers may be meltback from the high snowfall period of the mid-1940s to mid-1970s associated with the cool phase of the Pacific Decadal Oscillation.**

## INTRODUCTION

Glaciers grow or shrink appreciably due to decadal variations in ablation season temperature and accumulation season snowfall, and so can serve as visually compelling sentinels of climate change. Alpine glaciers advanced multiple times during the Holocene, most recently during the Little Ice Age; the last major glacial advance was in the mid-1800s (Grove, 2004; Matthews and Briffa, 2005). Portable cameras and glass plate negatives were invented at about that time, leading to the earliest photographs of alpine glaciers having been taken when they were close to their greatest sizes of the last few thousand years. Subsequently, alpine glaciers have generally retreated $10^2$–$10^3$ m, though at varying rates, and, in some cases, interrupted by small readvances. While the overall retreat of glaciers since the Little Ice Age is indisputable, measures are largely restricted to length or area (Orelemans, 2005), whereas direct measures of changing ice volume and mass are few (Huss et al., 2010).

Heightened interest in the scope, rates, causes, and potential consequences of climate change motivate improved measurements of its direct and derivative aspects, including quantities of ice and perennial snow and their rates of loss or gain. Here we assess changes in ice volume over the entire edifice of Mount Rainier, Washington State (United States), by differencing surface elevations between a high-resolution light detection and ranging (LiDAR) topographic survey performed in September–October 2007/2008, and the 10 m lateral resolution U.S. Geological Survey digital elevation model (DEM) derived from September 1970 aerial photography. Differencing these DEMs maps changes in ice surface elevation over a 37 to 38 yr period, and thereby the changes in ice and snow thickness and volume, including all of Mount Rainier's glaciers and perennial snowfields.

## GLACIERS OF MOUNT RAINIER AND THE PACIFIC NORTHWEST

Mount Rainier sustains the greatest concentration of glacial ice in the conterminous United States (~92 km$^2$, or ~16% of the total ice area exclusive of Alaska) including the largest glacier, the longest glacier, and the lowest terminus elevation (Driedger and Kennard, 1986; Krimmel, 2002; Fountain et al., 2007). Mount Rainier's glaciers were first written about in A.D. 1833, and were first mapped in their entirety in 1896 (Tolmie, 1833–1865; Russell, 1898). Due to their impressive size and ready accessibility, Mount Rainier's glaciers became a focus for glaciological studies (Heliker et al., 1984).

Mount Rainier's glaciers were close to their maximum Holocene sizes ca. 1850 (Sigafoos and Hendricks, 1972). They then retreated for a century until the mid-1940s or early 1950s, when retreat slowed, and many readvanced modestly through the early 1970s to middle 1980s; subsequently, most have been in retreat (Driedger, 1986; Nylen, 2004). Other Pacific Northwest glaciers behaved similarly, including on Mounts Baker, Hood, and Adams (Harper, 1993; Jackson and Fountain, 2007; Sitts et al., 2010), the Blue Glacier in the Olympic Mountains (Spicer, 1989), and with less continuous readvance, the South Cascade Glacier (Josberger et al., 2007). Slowed retreat and local readvance of Pacific Northwest glaciers were coincident with a cool phase of the Pacific Decadal Oscillation from ca. 1945 to ca. 1975 (Harper, 1993; Nylen, 2004; Josberger et al., 2007), with above average winter precipitation and below average winter sea surface temperatures along the Pacific Northwest coast (Mantua and Hare, 2002).

## METHODS

Severe rainfall in November 2006 led to widespread flooding across southwest Washington that extensively damaged infrastructure in Mount Rainier National Park. To aid in recovery and long-term planning, the National Park Service contracted for an aerial LiDAR topographic survey of Mount Rainier National Park (954 km$^2$). An area ~100 km$^2$ centered on Mount Rainier's summit was surveyed in September 2007, but inclement weather halted the effort, and the survey was completed in September–October 2008. Results averaged 5.73 laser points/m$^2$ over the main edifice and forested regions, with a vertical accuracy of 3.7 cm based on 2243 real-time kinematic control points on open flat road surfaces. Mean relative vertical accuracy is 11 cm as evaluated by comparisons of points on overlapping flightlines. Limits of ice and perennial snow were mapped utilizing both shaded relief and slope images of the bare-earth LiDAR DEM (Robinson et al., 2010).

Changes in ice area, elevation, and volume are referenced against the U.S. Geological Survey 1/3 arc-s (~10 m lateral spacing) DEM from the national elevation data set (http://ned.usgs.gov/). For the Mount Rainier area this DEM is derived from 1:24000 topographic maps produced by photogrammetry of September 1970 aerial photographs. Perimeters of glaciers and perennial snowfields in 1970 were digitized from the topographic sheets using georegistered scans of the hydrologic separates (Robinson et al., 2010). Most glacial terminii do not have simple shapes, so representative terminus retreat or advance ranges from 1970 to 2007/2008 are reported with no distinction between active and stagnant ice (Table 1).

Suitability of the LiDAR and 1970 DEMs for comparison was assessed from their apparent elevation differences exclusive of glacierized terrain, after coarsening both DEMs to coincident 100 m$^2$ pixels using a cubic-spline algorithm. Over the entire park, the coarsened LiDAR DEM averages 2.54 m low, exclusive of snow

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TABLE 1. GLACIER SIZE CHANGES FROM 1970 to 2007/2008, MOUNT RAINIER

| Name (sector) | 1970 area ($10^6$ $m^2$) | 2007/2008 area ($10^6$ $m^2$) | Mean elevation change (m) | Volume change ($10^6$ $m^3$) | Terminus change (m) |
|---|---|---|---|---|---|
| Winthrop (N) | 9.14 | 9.01 | –2.7 | –24.3 | +40 to –60 |
| Carbon (N) | 8.76 | 8.43 | –11.1 | –97.9 | –60 to –150 |
| Russell (N) | 3.29 | 2.98 | –5.7 | –18.7 | –60 to –180 |
| Inter (N) | 0.79 | 0.70 | –5.5 | –4.4 | –60 to –270 |
| Flett (N) | 0.56 | 0.53 | –2.6 | –1.5 | +25 to –90 |
| Curtis Ridge* (N) | 0.36 | 0.30 | –1.6 | –0.6 | –175 to –250 |
| Nisqually (S) | 4.56 | 4.25 | –20.3 | –93.5 | –60 to –360 |
| South Tahoma (S) | 2.81 | 2.01 | –8.1 | –23.2 | –2k to –2.3k |
| Kautz (S) | 1.77 | 1.54 | –10.9 | –20.2 | –630 to –700 |
| Wilson (S) | 1.61 | 1.54 | –9.4 | –28.3 | 0 to –60 |
| Paradise (S) | 1.08 | 0.76 | –12.3 | –13.7 | –15 to –90 |
| Muir (N) | 0.95 | 0.88 | –4.0 | –3.8 | 0 to –35 |
| Van Trump (S) | 0.66 | 0.55 | –8.5 | –6.6 | +50 to –85 |
| Pyramid (S) | 0.66 | 0.57 | –0.5 | –0.4 | +20 to –130 |
| Success (S) | 0.62 | 0.54 | –5.8 | –3.9 | –30 to –570 |
| Williwakas (S) | 0.18 | 0.16 | –9.4 | –2.0 | 0 to –60 |
| Emmons (E) | 11.08 | 11.28 | +1.2 | +13.8 | +440 to +570 |
| Ingraham (E) | 3.91 | 3.77 | –7.0 | –27.9 | –75 to –550 |
| Cowlitz (E) | 3.80 | 3.59 | –8.0 | –31.4 | –75 to –550 |
| Fryingpan (E) | 3.60 | 3.42 | +4.7 | +17.2 | 0 to –110 |
| Whitman (E) | 2.21 | 2.10 | –4.1 | –9.4 | 0 to –60 |
| Ohanapecosh (E) | 1.37 | 1.10 | –5.2 | –7.4 | –25 to –165 |
| Sarvent (E) | 0.52 | 0.46 | –6.3 | –3.5 | –15 to –65 |
| Tahoma† (W) | 8.23 | 7.69 | –10.0 | –83.3 | –180 to –225 |
| North Mowich (W) | 6.25 | 5.65 | –8.7 | –55.3 | –310 to –540 |
| South Mowich (W) | 4.49 | 4.23 | –6.7 | –30.4 | +110 to –150 |
| Puyallup (W) | 3.86 | 3.59 | –17.2 | –66.4 | –95 to –185 |
| Edmunds (W) | 1.38 | 1.24 | –8.8 | –12.1 | 0 to –115 |
| snowfields (all) | 4.59 | 3.93 | –2.6 | –14.7 | N.D. |
| Columbia Crest (all) | 0.18 | 0.17 | +1.1 | +0.2 | none |

*Note*: Sector—N, north; S, south; E, east; W, west.
*Small crevassed glacier on crest of ridge between Carbon and Winthrop Glaciers.
†Tahoma Glacier terminus retreat values for south tongue only.

and ice covered areas (root mean squared error, RMSE 10.2 m), but elevation mismatches are concentrated along forested canyon walls where both DEMs may be imprecise. Correspondence between DEMs is better tested by considering only elevations above treeline (>1600 m) where, exclusive of glacierized terrain, the coarsened LiDAR DEM averages 0.72 m low (RMSE 8.2 m). The September 1970 aerial photographs show that the upper mountain carried heavy new snow, concealing the limits of small ice-filled couloirs and ice slopes, raising the 1970 DEM above that of bare rock, and accounting for some of the 0.7 m elevation mismatch.

## CHANGES IN GLACIER THICKNESS, LENGTH, AREA, AND VOLUME

### Thickness and Length

Mapped differences in the surface elevation of glacial ice and snowfields form coherent patterns for the edifice as a whole and along individual glacier systems (Fig. 1; Table 1; GSA Data Repository[1]). All but 2 of the 28 named glaciers and crevassed snowfields have thinned and shortened in their terminal regions. Pronounced thinning (>15 m, locally to 90 m) is mainly restricted to elevations <2000 m (Figs. 1 and 2A), and glaciers that terminate at higher elevations (Flett, Russell, Inter, Whitman, Edmunds, Fryingpan, Curtis Ridge) thinned and shortened the least. The large Winthrop and Emmons Glaciers on the north to northeast flank of the mountain are exceptions, both having thickened substantially (>35 m) near their terminii, and the Emmons Glacier also advanced. Their anomalous behavior was discerned previously from aerial photographs and attributed to insulation by rockfall events (Driedger, 1986; Nylen, 2004), notably in 1963 (Emmons Glacier) and 1989 (Winthrop Glacier).

Exposure aspect influences glacier wastage. Large south-facing glaciers (Kautz, Nisqually) thinned appreciably (>15 m) over broad areas at elevations to 4200 m, whereas around the rest of the mountain glaciers at 3000–4000 m elevation remain largely unchanged or have thickened moderately (<15 m) (Fig. 1). Susceptibility of south-facing glaciers to thinning is also recorded by the most southerly facing glaciers (Nisqually, Wilson, and Paradise) having the greatest areally averaged reductions in surface elevation (Table 1). Profiles of average thickness change versus elevation, for glaciers grouped by aspect, show an overall pattern of diminished thinning with increased elevation to 3000 m (Fig. 2), with low elevation exceptions due to terminal thickening of the Winthrop and Emmons Glaciers. On the south and, locally, north flanks the thinning increases again above 3000 m before diminishing to near zero approaching the summit. On the south flank this zone of high elevation thinning is localized to, and slightly above, where the glaciers pass as narrow icefalls though rock headwalls, whereas on the north flank it is restricted to a shallow trough along the northwest margin of the Winthrop Glacier adjacent to Curtis Ridge.

The elevation difference map also shows a finer structure consisting of alternating greater and lesser thickness change along lower glacier reaches, most clearly along the lower Winthrop, Emmons, and Cowlitz Glaciers, and less obviously along the lower Tahoma, South Tahoma, Puyallup, and South Mowich Glaciers (Fig. 1). Wavelengths of these along-glacier anomalies scale roughly with glacier size: 1–2 km on the large Emmons and Winthrop Glaciers, ~1 km on the Cowlitz Glacier, and 0.3–1 km along the smaller glaciers. These alternating elevation changes along the lower glacier reaches may be interference patterns produced by differencing between kinematic waves on the 1970 versus the 2007/2008 glacier surfaces. Localized regions of thinning are also present on many of the glaciers, many situated at or just below crevassed steep slopes and icefalls where the albedo is low due to exposure of dirty ice.

### Area

Driedger and Kennard (1986) estimated 92.1 $km^2$ of glacial ice and perennial snow at Mount Rainier from the 1970-based U.S. Geological Survey topographic sheets. We obtain 93.3 $km^2$ for 1970 (Table 1), a slightly larger value probably because computers allow easier inclusion of small snow patches and glacier details. By 2007/2008, the total area of ice and perennial snow had shrunk to 87.0 $km^2$, or a loss of 6.7% of the 1970 value. The single greatest area loss by far, –0.8 $km^2$, was from the South Tahoma Glacier, where a tongue of ice below 1900 m elevation melted away, and the only glacier to have enlarged is the Emmons, and that only slightly, +0.2 $km^2$. The combined area loss from south-facing glaciers and crevassed snowfields is greater than for any other sector in both absolute (2.1 $km^2$) and proportional to 1970 terms (14.1%), followed by those that face west (1.8 $km^2$, 7.5%), north (0.96 $km^2$, 4.2%), and east (0.77 $km^2$, 2.9%); the remaining area loss is from widely scattered perennial snow patches.

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[1] GSA Data Repository item 2011257, digital map of surface elevation changes 1970–2007/2008 for glaciers and snowfields at Mount Rainier, Washington, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

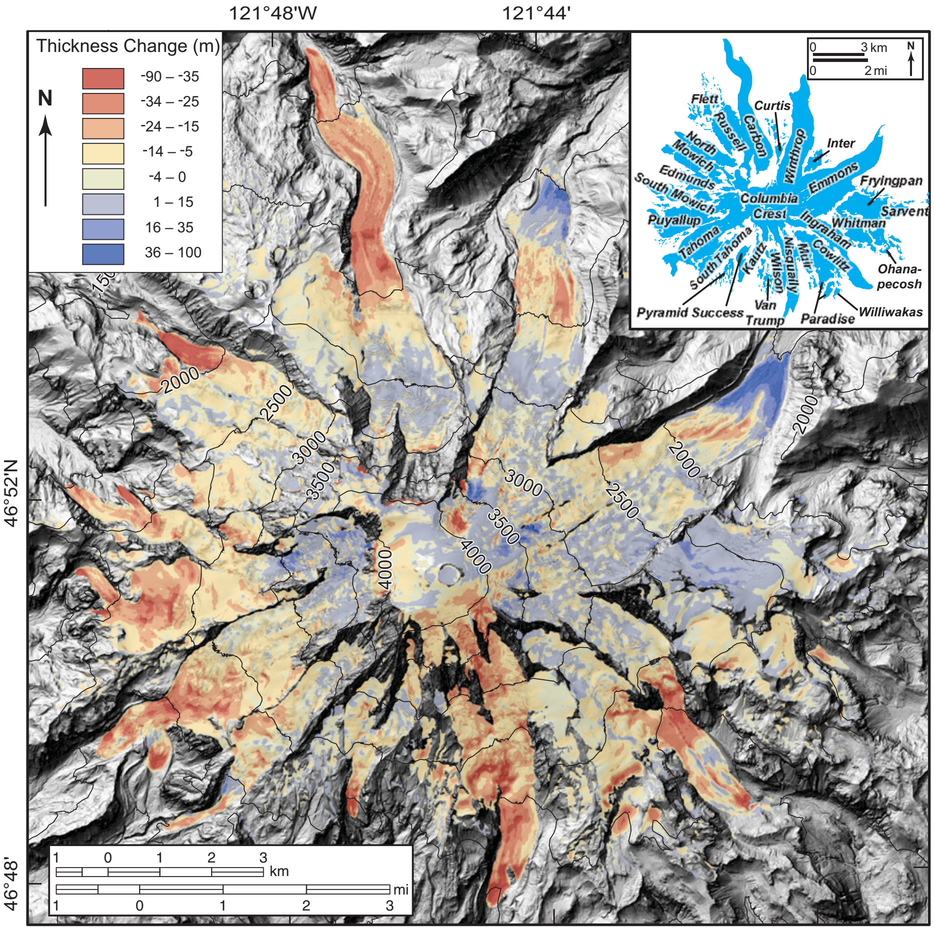

**Figure 1. Map of net change in surface elevation of glaciers and snowfields from 1970 to 2007/2008 at Mount Rainier, Washington (colored), derived by digital elevation model (DEM) differencing (see footnote 1). Apparent elevation differences outside of snow- and ice-covered areas are omitted for clarity. Elevation contours (500 m) and background shaded relief are from LiDAR (light detection and ranging) DEM (Robinson et al., 2010). Marginal ticks give north latitude and west longitude. Inset shows index map and names of glaciers and perennial snowfields (blue) at Mount Rainier.**

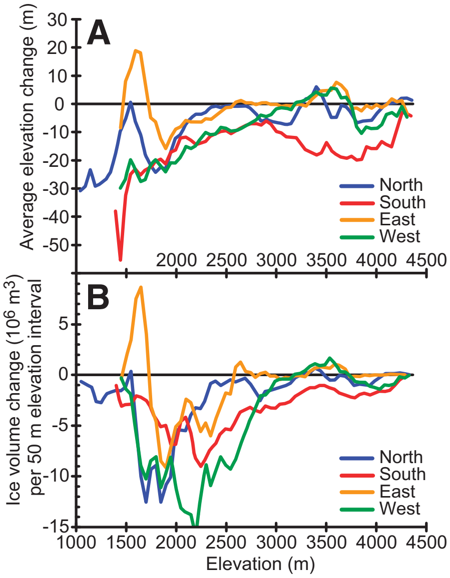

**Figure 2. A: Average ice thickness changes 1970 to 2007/2008 versus surface elevation for glaciers and crevassed snowfields grouped by exposure aspect (Table 1) and shown for 50 m altitude interval steps. B: Volume changes. Low-elevation thickness and volume anomalies in north and east sectors are due to terminal thickening of Winthrop and Emmons Glaciers.**

## Volume

Simple differencing between the 1970 and 2007/2008 DEMs in the area of perennial snow and ice gives a net volume change of –0.65 km$^3$ (Table 1). Because the 1970 DEM may be up to 0.7 m high relative to the LiDAR, a minimum net volume change is –0.59 km$^3$. Driedger and Kennard (1986) estimated 4.42 km$^3$ of ice and perennial snow at Mount Rainier, as derived from 1981 radar soundings of the Nisqually, Carbon, Tahoma, Russell, and Emmons Glaciers, combined with semiempirical area-volume scaling utilizing 1970 areas. Mount Rainier's glaciers and perennial snowfields have therefore lost ~14.7% to 13.4% of their 1970–1981 composite volume.

All of Mount Rainier's named glaciers and crevassed snowfields lost volume over the 1970 to 2007/2008 interval, except for the Fryingpan and Emmons Glaciers on the east flank, and minor crater-filling snows of Columbia Crest near the summit (Table 1). The Carbon Glacier lost the greatest net volume of any single glacier on Mount Rainier (0.1 km$^3$; volumes hereafter from simple differencing of DEMs), which was unexpected because the Carbon Glacier descends the most north-facing slope of the mountain, it shortened only moderately (60–150 m), and it shrank in area by an intermediate amount (0.33 km$^2$), similar to many other glaciers that lost substantially less volume. That the Carbon Glacier lost such volume may stem from its extending to the lowest elevation of any of Mount Rainier's glaciers (1075 m), and to its having a large area <2000 m elevation, whereas its minimal shortening may be due to its atypically great thickness (Driedger and Kennard, 1986). The Carbon Glacier fills a deep, steep-sided canyon at relatively low elevation and so loses volume by lowering its surface without commensurate terminus retreat or reduction in surface area.

Noteworthy also is the contrast between the adjacent Emmons and Winthrop Glaciers, both of which thickened in their terminal regions (Fig. 1); the Emmons Glacier also advanced and increased in volume slightly (Table 1). That the Winthrop Glacier lost volume despite its terminal thickening shows that it behaved similarly to nearly all other glaciers on Mount Rainier and supports the inference that low-elevation thickening was due to insulation by rockfall debris (Driedger, 1986; Nylen, 2004). The Emmons Glacier divides from the Winthrop at ~2800 m elevation and is flanked to the east by the Fryingpan Glacier, which also grew slightly (Table 1). The lower Emmons Glacier was thickly carpeted by rockfall debris in 1963 (Crandell and Fahnestock, 1965), but the Fryingpan Glacier lacks rockfall cover, raising the likelihood that local climatic factors preferentially sustained glaciers on the mountain's east flank. Despite having undergone net growth, the terminus of the Fryingpan Glacier retreated locally (0–100 m) and snowfields fed by collapse of its terminal ice cliffs have largely melted away.

Net changes in ice volume also differ with exposure direction. Cumulatively, east-flank glaciers lost the least volume (–0.05 km$^3$), followed by those that face north (–0.15 km$^3$), south (–0.20 km$^3$), and west (–0.25 km$^3$). That south-flank glaciers lost the greatest mean surface elevation and area, but did not lose the most volume, is reconciled by the low total ice area on the south flank (15%–16%). Greater areas of ice on the west flank led to a greater net volume loss. The east sector is again distinct, having the largest ice area (30%), but the least volume loss.

Volume change with elevation can be examined using a standard elevation interval (50 m). Curves of volume change versus elevation are similar for the different sectors (Fig. 2), attaining zero at the lowest and highest elevations where the glacier termini and sources taper, and with volume-loss maxima centered from 1750 m (north flank) to 2250 m (south flank).

## IMPLICATIONS

### Causes of 1970 to 2007/2008 Glacier Volume Changes at Mount Rainier

Glaciers melt mainly because of solar irradiation and ambient temperature during the ablation season, a simple approximation being:

$$\frac{dh}{dt} = \mathrm{a}T + \mathrm{b}(1-\alpha)\varepsilon, \qquad (1)$$

where $h$ is glacier thickness, $t$ is time, $T$ is temperature above the melting point, $\varepsilon$ is the aspect-adjusted solar irradiance, $\alpha$ is albedo, and a and b are constants (Pellicciotti et al., 2005). If Mount Rainier's glaciers were in steady state, and summertime temperatures increased regionally with no changes in irradiance or winter snowfall, this expression would predict that all sides of the mountain would lose ice equally. That south-facing glaciers have thinned more and to higher elevations than those on other flanks, and that ice thickened on many areas of the upper mountain, shows that other factors were involved.

Preferential melting of south-flank glaciers can alternatively be thought of as a recovery from a precipitation anomaly, just as snowfall melts away fastest on hillsides facing the sun due to their higher $\varepsilon$ values. The modest advance of many Pacific Northwest glaciers bracketed between the late 1940s and early 1980s corresponds with generally above average snowfall measured at Paradise on Mount Rainier's south flank (Western Regional Climate Center, http://www.wrcc.dri.edu), and by proxy, as above average river discharges in the region during the snowmelt season (U.S. Geological Survey records, http://waterdata.usgs.gov/wa/nwis/monthly). Since ca. 1976, snowfall and discharge have returned to near long-term average values, and snow and ice melted preferentially on Mount Rainier's south flank due to its greater solar irradiance. Ablation season temperatures at Mount Rainier were not in phase with the period of high-snowfall winters, being generally warmer than historic averages from at least 1920 to 1961, generally cooler than average through 1984, and since fluctuating around the historic mean (Western Regional Climate Center; PRISM, http://www.prism.oregonstate.edu). That differential glacier thinning may be a recovery from a high-precipitation anomaly does not negate long-term temperature increases as the primary cause of glacial retreat since the Little Ice Age (Oerlemans, 2005).

### Future of Ice at Mount Rainier

The net loss of 14 vol% of Mount Rainier's ice and perennial snow over a 37/38 yr period would seem to bode ill for the long-term survival of its glaciers, with consequences for recreation, water supplies, electric power generation, wildlife habitat, sediment transport, and flooding. However, Mount Rainier's glaciers were of a size similar to today in the late 1940s to late 1950s, before their approximately three decades of modest expansion, and then retreat to their present sizes (Heliker et al., 1984; Driedger and Kennard, 1986; Driedger, 1986; Nylen, 2004). This temporary regrowth shows that Mount Rainier's glaciers are sensitively balanced and have the potential to enlarge again with modest changes in precipitation and temperature. This temporary regrowth was, however, superimposed on a long-term trend of decreasing ice volume that commenced with the end of the Little Ice Age (Sigafoos and Hendricks, 1972). The interval considered in this study includes as much as 10 yr of the period of glacier regrowth (Nylen, 2004), so the average rate of ice loss since ca. 1980 is >0.4 vol%/yr. Precise DEMs constructed by photogrammetry of aerial images collected between 1970 and 2007/2008 could refine estimated rates of volume change.

The 2007/2008 LiDAR topography also provides a high-resolution baseline against which subsequent surveys can be referenced, revealing detailed changes in ice surface elevation and volume. Future whole-edifice surveys by LiDAR or other methods will better show the rates of ice volume change, and where on the mountain in terms of elevation and aspect. Issues to track and develop monitoring programs for include if and why the north-flank Carbon Glacier continues to dominate ice loss, east-flank glaciers continue their modest preservation and/or expansion, and south-flank glaciers continue their pronounced thinning. Because glaciers on Mount Rainier and other major Cascade volcanoes face all points of the compass rose, and glacier-bearing Cascade volcanoes span ~8.5° of latitude along the Pacific coast of North America, the region is well suited to reveal influences of latitude and aspect on ice preservation.

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