Field Mapping Glacier Extents at Mount Rainier for Hazard Recognition

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Introduction

The goal of this report is to describe the role glaciers play in the local and regional hydrology and the impact they may have on the environment and infrastructure of Mount Rainier National Park. Methods included field verification of the spatial extent of debris-covered ice, observing the velocity of debris-covered ice using both field techniques as well as remote sensing techniques, and estimating volume change of glacier ice using airborne LiDAR digital elevation models.

Background

Mount Rainier is a 4,395 m high stratovolcano that supports the largest concentration of glacier ice in the United States exclusive of Alaska (Krimmel, 2002). There are 143 glaciers and permanent snowfields on Mount Rainier with a total area of 83.3 km^2, 27 of these are named glaciers (82.1 km^2) (Nylen, 2004). With glacier ice spanning from the summit down to 1,075 m, Mount Rainier is home to the largest glacier (Emmons Glacier, 11.2 km^2), the longest glacier (Carbon Glacier, 8.2 km), and the lowest glacier terminus (Carbon Glacier, 1,070 m) in the coterminous United States (Krimmel, 2002). The glaciers on Mount Rainier have a total ice volume of 4.4 km^3 (Driedger and Kennard, 1987). Nylen (2004), among others, recognized the importance of quantifying the spatial extent of debris-covered ice as it is a major influence on ablation and can contribute to glaciers extending further down valley than if they were clean. Nylen (1994) found that Carbon Glacier had the highest fractional area of debris-covered ice at 45%, followed by Emmons Glacier at 30%, Cowlitz Glacier at 24%, and Nisqually Glacier at 23%.

S.F. Emmons and A.D. Wilson were the first to document the glaciers of Mount Rainier as a part of the Fortieth Parallel Corps under the direction of Clarence King (Brockman, 1938). The first to recognize the recession of glaciers at Mount Rainier was I.C. Russell in the 18th Annual Report of the United States Geological Survey (1897):

> *"Every glacier about Mount Rainier that was examined by the writer furnished evidence of a recent recession of its terminus and a lowering of its terminus. In two instances – the Carbon and the [North Mowich] Glaciers – rough measurements of the amount of these changes during the past fifteen years were obtained."*

Nylen (2004) observed a pattern of overall glacier retreat intermixed with short periods of glacier advance that was consistent with trends in global and regional climate and mirrored the global behavior of glaciers (Haeberli et al., 1998). The trend of continued glacial recession combined with the extensive debris-cover left a periglacial environment that consists of large amounts of thick, unconsolidated sediments. The steep slopes of the glacially shaped valleys creates an environment ripe for mass wasting and producing debris flows. The large amount of unconsolidated sediment and potential for rapid infusions of water from glacial melt or rain on glaciers producing floods (outburst and otherwise) that mobilize sediment.

Studies of debris flows showed that almost all debris flows from the South Tahoma Glacier initiated from glacier outburst floods (Walder and Driedger, 1995). Debris flows were observed as dry season events and rain induced wet season events. They found a strong relationship between maximum daily air temperature and precipitation and outburst flood occurrence. They also recognized the role of debris-laden stagnant ice in developing debris flows as a source of melt water and unconsolidated debris. Recent investigations by National Park Service personnel suggest that this phenomena is not limited to South Tahoma Glacier and in fact could be observed on many of the large debris covered glaciers of Mount Rainier.

This study focuses on the 11 of the major glaciers of Mount Rainier. This includes the 9 largest glaciers on Mount Rainier, as well as South Tahoma Glacier and Kautz Glacier. All glaciers are greater than 1.9 km^2 and many have evidence of mass wasting and debris flow initiation points.

Methods

Stagnant Ice & Glacier Velocity

Prior to the beginning of the summer field season, orthorectified aerial photographs acquired by the National Agricultural Imagery Program (NAIP) in 2009 and 2011 were compared to detect surface motion on debris-covered ice. Visual examination of the images identified large boulders on the surface. The boulder location was recorded for each image and displacement was calculated; elapsed time was determined from the photo dates, and mean ice velocity was calculated. Additional air photos taken by the Washington Department of Transportation in 2007 were orthorectified and examined for glacier motion and glacier recession.

In addition, glacier velocity was measured in the field during the summer of 2012 by repeat GPS measurements. A Trimble GeoXh GPS unit was used to measure the location of large boulders on the glaciers surface in early summer, and again later in the season, yielding a mean summer surface velocity. Boulders were chosen for their large size and unique appearance and pictures were taken to aid in finding the boulders again. The location of the measurement on the boulder was marked with yellow flagging or yellow tape to reoccupy the precise spot where the first measurement was recorded. GPS measurements were post-proccesed by Mount Rainier National Park staff.

Mapping Glacier Extent

The spatial extent of glacier ice on Mount Rainier has been mapped over the past century (Brockman, 1938; Nylen, 2004; Sisson et al., 2011). The more recent efforts have relied on remote sensing primarily from oblique and vertical aerial photographs. In many regions, aerial photographs more than adequately capture the spatial extent of glacier ice. However, on Mount Rainier where thick debris cover obscures much of the glacier extent at lower elevations, aerial photographs often cannot clearly define the glacier boundaries. During the 2012 summer field season, many of the larger glaciers on Mount Rainier were visited to confirm results of the aerial-based glacier outlines. Where possible, observations were made of exposed ice in the rock debris indicating the presence of buried ice. When buried ice was found, its location was marked with a GPS. In cases where large ice fronts were exposed, such as at the active glacier terminus, GPS was used to digitize the glacier margin.

Glacier area was calculated by adjusting the glacier margins from a previously existing glacier inventory that was created based on 2009 NAIP imagery. This saved significant time by not having to digitize the glacier boundaries on the upper flanks of the mountain and reduced the unnecessary associated errors from such a task. Glacier recession, a linear distance was also calculated because over short time periods (> five years) total surface area changes little relative to the uncertainty in the area estimate. Linear recession provides a better estimate of short term glacier change. It was measured as the mean distance between terminus positions digitized from the imagery.

Volume Change

Sisson et al., (2011) estimated ice volume change using the United States Geological Survey DEM from 1970 and LiDAR collected in 2007 and 2008. We update these volume change estimates using our corrected glacier margins and the same 1970 DEM and 2007/2008 LiDAR. Additionally, we use LiDAR collected in late summer 2012 for the South Puyallup River drainage, Tahoma Creek drainage, and Kautz Creek drainage to calculate recent volume change for the terminus areas of the Tahoma, South Tahoma, and Kautz glaciers.

Results

Stagnant Ice & Glacier Velocity

The 2007 imagery was acquired by the Washington Department of Transportation (WSDOT) in September 2007. The imagery was orthorectified with the Leica Photogrammetry Suite (LPS), a part of the ERDAS Imagine software family, using the 2009 NAIP imagery as a horizontal reference for ground control point coordinates and the 2007/2008 LiDAR DEM as a vertical reference. The orthorectified 2009 and 2011 NAIP imagery had less than 10% cloud cover. The spatial resolution is 1 m and a horizontal accuracy within 6 m of ground control points. The 2007 WSDOT imagery was acquired with better than 1 meter ground resolution and with less seasonal snow cover than the 2009 imagery. Unfortunately the 2011 imagery exhibited extensive snow cover. The deciding attribute for utilizing the imagery for feature tracking was the surface definition of the debris-cover and sun angle. If the surface definition was poor and the sun angle didn't create sufficient shadows, it was impossible to identify individual large boulders for feature tracking. In addition, seasonal snow cover had to be minimal over the debris-cover to make the boulders visible.

Using the 2007 and 2009 imagery, Cowlitz Glacier is the only glacier with the adequate surface definition and limited seasonal snow for feature tracking. Using the 2009 and 2011 imagery, Emmons , Winthrop, and Carbon glaciers were all snow free, but only Emmons and Winthrop glaciers have sufficient surface definition. Results from feature tracking (2009 – 2011) indicate a mean velocity of 2.1 ± 5.7 cm d^{-1} for Emmons Glacier and 3.5 ± 5.2 cm d^{-1} for Winthrop Glacier. Cowlitz Glacier had a mean velocity of 3.5 ± 4.0 cm d^{-1} (2007 - 2009) (Table 1). The high uncertainty values relative to the mean velocity suggest a lack of significance to the data collected by feature tracking.

GPS measurements of glacier velocity were made for six glaciers during summer 2012. Mean glacier velocities ranged from a low of 0.9 ± 1.4 cm d^{-1} for Tahoma Glacier with no apparent glacier motion at the terminus, to a high of 4.5 ± 1.3 cm d^{-1} at Carbon Glacier where measured ice velocity exceeded 10 cm d^{-1} at some points on the glacier surface. Tahoma Glacier is the only glacier where the data indicate a stagnating terminus. The uncertainty about the surface velocity on North Mowich Glacier is much higher than for other glaciers, rendering the velocities insignificant. However, the vector map of the velocity data suggests that North Mowich Glacier is not stagnating. Results from feature tracking agree with field measurements (GPS) of velocity. Winthrop Glacier shows the most inconsistency between feature tracking and field measurements; feature tracking yielded 3.5 ± 5.2 cm d^{-1} while field measurements yielded 2.5 ± 0.7 cm d^{-1}.

Table 1 - Summary of surface ice velocities for 6 glaciers derived from feature tracking and GPS.

Source	Glacier	Number of Points	Mean Velocity (cm d^{-1})	Std. Dev.	Median Velocity (cm d^{-1})	Max Velocity (cm d^{-1})	Min Velocity (cm d^{-1})
Feature Tracking	Cowlitz	12	3.5 ± 4.0	1.9	4.1	5.6	0.3
	Emmons	25	2.1 ± 5.7	1.0	2.2	3.7	0.5
	Winthrop	21	3.5 ± 5.2	1.4	3.3	6.0	0.9
GPS	Carbon	30	4.5 ± 1.3	3.8	3.1	13.3	0.3
	Cowlitz	16	3.3 ± 1.0	2.0	3.8	6.1	0.2
	Emmons	21	2.4 ± 1.4	1.7	1.8	6.7	0.3
	North Mowich	26	2.1 ± 2.7	1.0	2.3	4.0	0.2
	Tahoma	25	0.9 ± 1.4	1.0	0.6	5.4	0.1
	Winthrop	22	2.5 ± 0.7	1.7	1.9	5.7	0.5

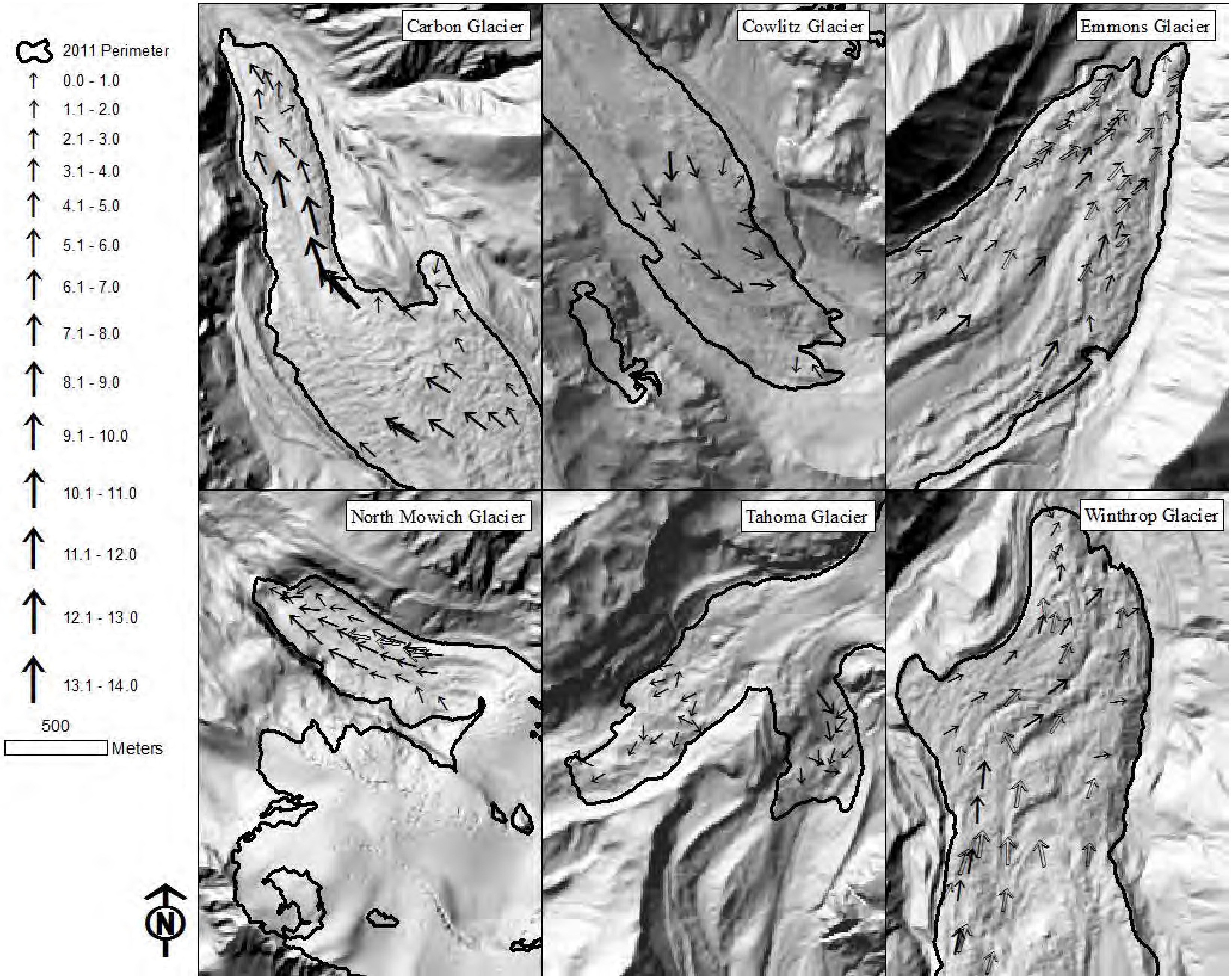


Figure 1 - Map of glacier surface velocity vectors. Open arrows indicate remote sensing method while solid arrows GPS measured surface velocities.

Glacier Extent

Efforts to field-verify the extent of debris-covered glacier ice confirmed that manually interpreted aerial photographs from recent inventories provided reliable estimates of the glacier perimeter within a reasonable level of uncertainty (Nylen, 2004; Sisson, 2011). However, defined glacier extent in those same inventories was inconsistent with field-verified glacier perimeters for Tahoma, South Tahoma, and Kautz glaciers near the glacier terminus. Tahoma Glacier has a terminus that is covered in thick, hummocky debris and was difficult to map in the field. South Tahoma and Kautz glaciers are both remote glaciers with steep termini and were field verified from safe vantage points. Mapping either of these glaciers directly would have been extremely risky. Corrected perimeters of Nylen (2004; 2009) and of Sisson (2011) using 2011 imagery and field data collection in 2012 resulting in updated and corrected areas are summarized in Table 2. The extent of debris cover on the glaciers is summarized in Table 3. The landscape in the 2011 NAIP imagery was too snow-covered to attempt quantifying debris cover. In contrast, the 2009 is much better for quantifying debris cover.

Table 2 - Summary of glacier area from various inventories including updated outlines from this study. All values are in square kilometers.

Glacier	1994 (Nylen, 2004)	2007/2008 (Sisson et al., 2011)	2009 (Nylen, unpub.)	2011
Carbon	7.98 ± 0.08	7.65	7.40	7.39
Cowlitz	7.70 ± 0.10	7.28	7.05	7.03
Emmons	11.22 ± 0.08	11.23	10.99	10.98
Kautz	2.20 ± 0.04	2.06	2.08	2.07
North Mowich	6.11 ± 0.10	5.40	5.29	5.28
Puyallup	4.35 ± 0.05	3.51	3.52	3.52
South Mowich	4.06 ± 0.07	3.97	3.97	3.97
South Tahoma	2.23 ± 0.03	1.97	2.02	2.10
Tahoma	7.28 ± 0.08	6.95	6.83	7.15
Winthrop	9.95 ± 0.07	8.41	8.53	8.47

Table 3 - Summary of glacier area and debris-cover in 2009 for Mount Rainier National Park, based on 2009 NAIP imagery. Carbon Glacier has the largest fraction of debris cover.

Glacier	Area (km^2)	Debris Covered Area (km^2)	Debris Cover (%)	Length (km)
Carbon	7.39	3.45	46.7%	8.4
Cowlitz	7.03	1.25	17.8%	7.4
Emmons	10.98	2.38	21.7%	7.7
Kautz	2.07	0.16	7.7%	4.0
North Mowich	5.28	0.54	10.2%	4.5
Puyallup	3.52	0.47	13.4%	4.5
South Mowich	3.97	0.95	23.9%	6.0
South Tahoma	2.10	0.35	16.7%	3.2
Tahoma	7.15	1.45	20.3%	6.8
Winthrop	8.47	2.55	30.1%	7.9

The linear recession was calculated from the orthorectified imagery in 2007 (WSDOT), 2009, and 2011 (NAIP) (Table 4).

Table 4 – Average change in terminus positions between 2007 and 2011.

Glacier	2007 to 2009 (m)	2009 to 2011 (m)
Carbon	-30	-30
Cowlitz	-20	-30
Emmons	-5	-20
Kautz	-	-
North Mowich	0	-15
Puyallup	0	-30
South Mowich	-35	-15
South Tahoma	-	-
Tahoma	-40	-10
Winthrop	0	0

Volume Change

Volume change estimates were updated from those made by Sisson et al. (2011) using the updated glacier boundaries from this study and the LiDAR collected in the Fall of 2007 and 2008. Results from this study were inconsistent with those of Sisson et al (2011). An attempt to reproduce the results of Sisson et al (2011) were not successful, likely due to differing methods of reprojecting the original DEM from the 1927 datum to the 1983 datum. Although we can't reproduce the results of Sisson et al (2011), the differences between results may the result of choosing to use different geographic transformations to reproject the 1970 DEM from NAD 1927 to NAD 1983. Although the absolute values of volume change differ between this study and that of Sisson et al (2011), the pattern of thickness change between both studies is nearly identical. This supports the conclusion that the transformation between datums was the primary cause of the variation.

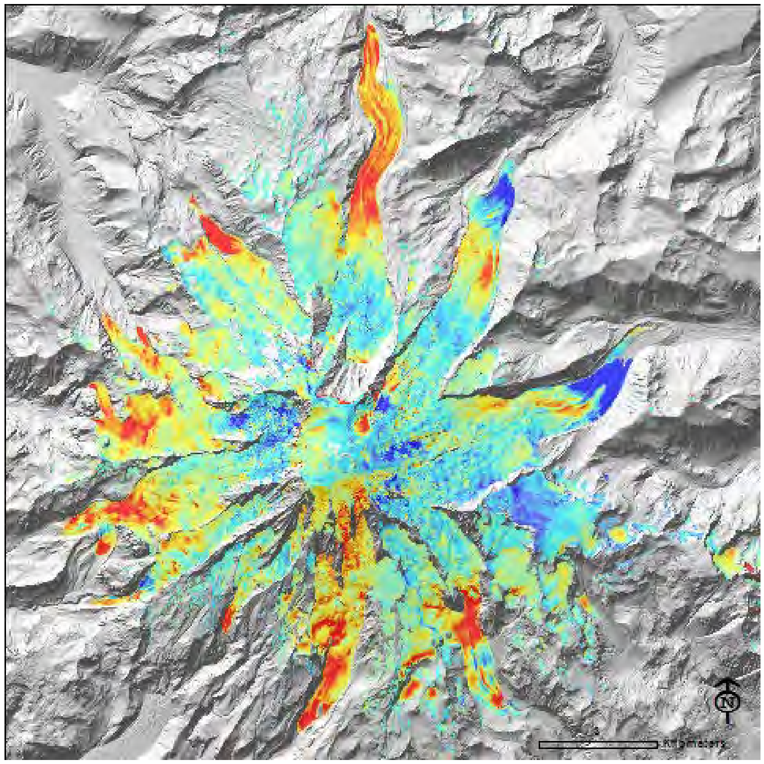
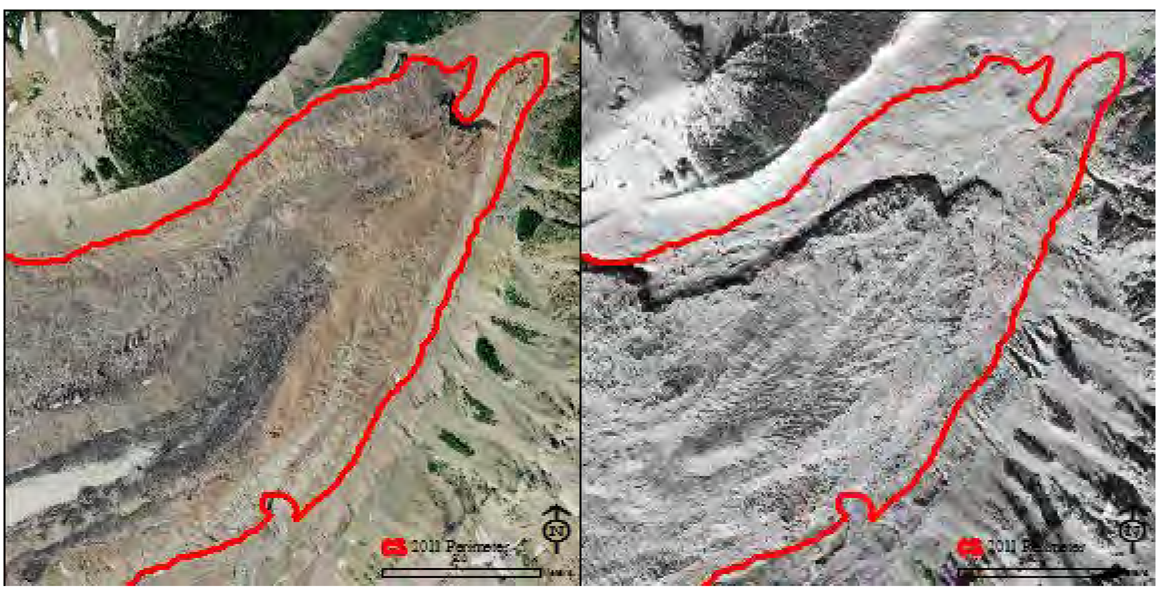


Figure 2 - Map of thickness change (this study) from 1970 to 2007/2008.

Table 5 - Summary of volume change from Sisson et al (2011) and this study. Specific Mass Loss is calculated for data from this study.

Glacier	Sisson et al., 2011 10^6 m^3	This Study 10^6 m^3	Difference 10^6 m^3	Difference (%)	Specific Mass Loss (m)
Carbon	-97.9	-88.8	-9.1	-9.3%	-10.97
Cowlitz	-31.4	-55.1	23.7	43.0%	-7.12
Emmons	13.8	-7.1	20.9	48.6%	-0.62
Kautz	-20.2	-16.2	-4.0	-19.8%	-6.26
North Mowich	-55.3	-32.6	-22.7	-41.0%	-5.24
Puyallup	-66.4	-48.7	-17.7	-26.7%	-12.52
South Mowich	-30.4	-6.0	-24.4	-80.3%	-1.34
South Tahoma	-23.2	-10.2	-13.0	-56.0%	-3.45
Tahoma	-83.3	-41.2	-42.1	-50.5%	-5.31
Winthrop	-24.3	-42.9	18.6	43.4%	-4.61

All of the glaciers examined in our study lost volume between 1970 and Fall 2007 and Fall 2008. North-facing Carbon Glacier lost the most ice volume, -88.8 10^6 m^3 and the second greatest specific mass loss (-10.97 m). Puyallup had the greatest specific mass loss, -12.52 m. South Mowich Glacier lost the least -6.0 10^6 m^3 and the second greatest specific mass loss (-1.34m), whereas Emmons lost the least specific mass (-0.62m). Although both Emmons and Winthrop glaciers lost volume, both of these glaciers advanced during the same time period. Between 1970 and 2007, the Emmons Glacier advanced up to 600 m while the Winthrop Glacier advanced up to 200 m (Figure 3). Two likely explanations for the advance of Emmons and Winthrop glaciers include rockfall insulating the glacier surface and decreasing ablation, allowing for an advance of the terminus positions, or a kinematic wave. We know that Emmons experienced a major rockfall in the 1960's that covered a portion of the glacier and that debris has translated to the ablation zone in the best decade or so.



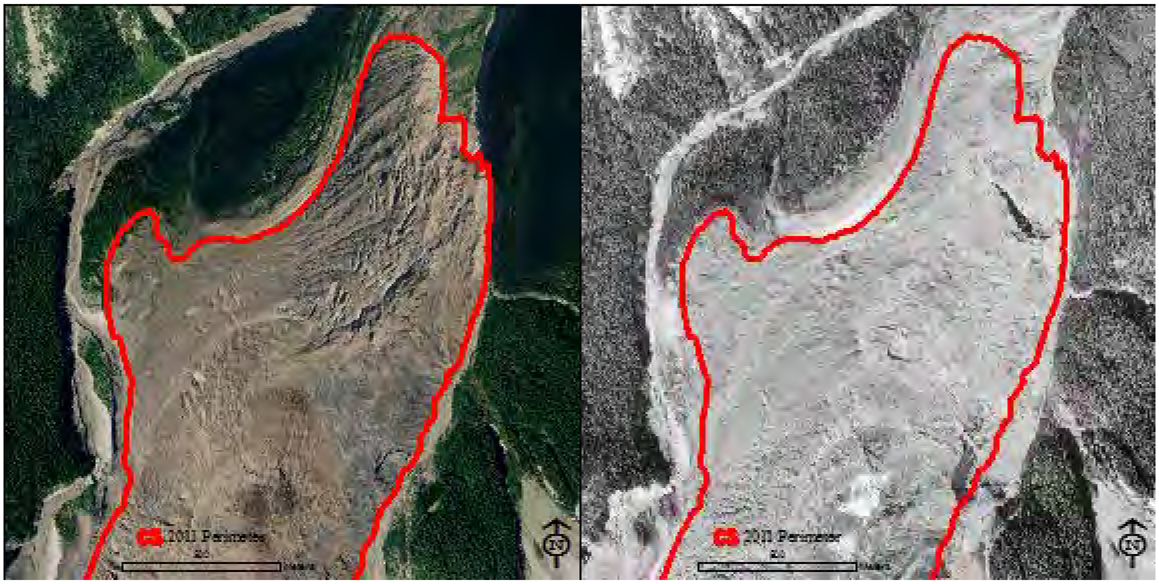


Figure 3 - Emmons Glacier (top) and Winthrop Glacier (bottom) in 2009 (left) and 1970 (right). Both glaciers advanced during this time period. The glacier perimeter in 2011 is shown in red.

In September 2012, airborne LiDAR data was collected for the South Tahoma drainage and the Kautz drainage. Although the focus of these missions was to investigate river erosion and aggradation, the LiDAR data included the lower ablation zones of Tahoma, South Tahoma, and Kautz glaciers. These data were compared to the 2007/2008 LiDAR to determine short-term ice thickness change (4-5 years) and to investigate the utility of short term repeat LiDAR for investigating the boundaries of debris covered ice.

Tahoma Glacier had an average thickness change of -3.6 m between 2007/2008 and 2012 (Figure 4). Ice thinning was apparent even in heavily debris-covered areas of the terminus. The lowest stagnant part of the terminus thinned by an average of -2.8 m, while the main part of the north terminus thinned by an average of -10.3 m. The south fork of the Tahoma Glacier terminus thinned by an average of -6.9 m.

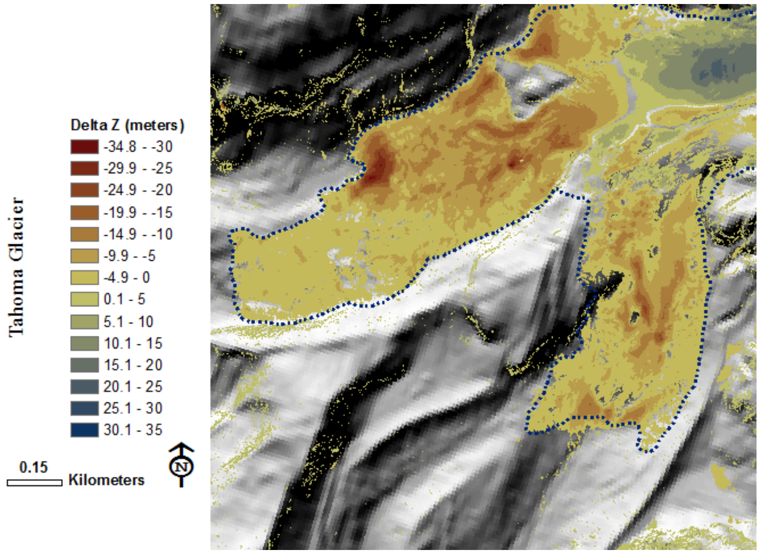
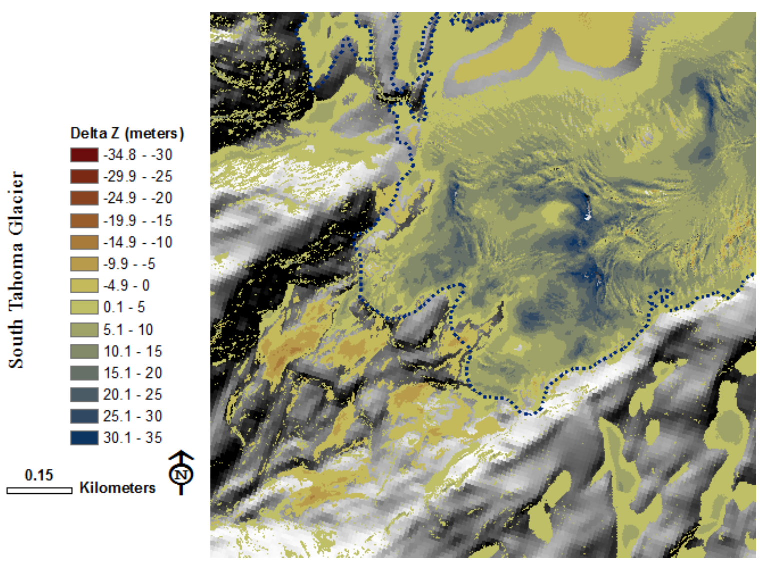


Figure 4 – Map of thickness change for the Tahoma terminus and surrounding area from 2007/2008 to 2012. Glacier boundary is defined by dotted line.

South Tahoma and Kautz glaciers both terminate at higher elevations and have much greater slopes at their terminus positions. These glaciers differ from other glaciers on Mount Rainier glaciers like Carbon Glacier or Tahoma Glacier where the glacier terminates at low elevation at fairly low slopes and is heavily debris-covered in the ablation zone. South Tahoma Glacier thickened by an average of 9.2 m while Kautz thickened by 3.6 m. Due to the high elevation termini and steep terminal slopes, both glaciers calve off ice from steep terminal faces rather than slowly ablate in a traditional ablation zone.



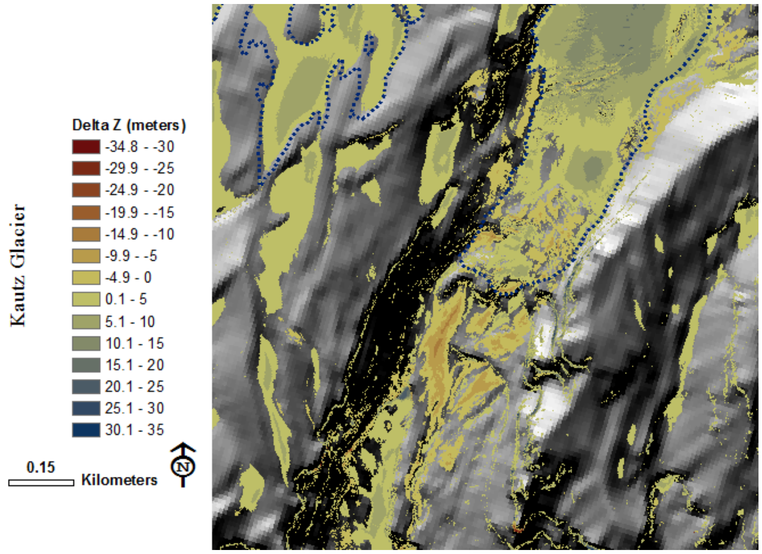


Figure 5 - Map of thickness change in the ablation zone for the South Tahoma Glacier (top) and Kautz Glacier (bottom) from 2007/2008 to 2012. Glacier boundary is defined by dotted line.

Table 6 – Mean thickness change in the ablation zone for Tahoma, South Tahoma, and Kautz glaciers from 2007/2008 to 2012.

Glacier	Mean Thickness Change (m)	Terminus Area (km^2)
Tahoma	-3.6	0.88
South Tahoma	9.2	0.28
Kautz	3.6	0.22

Discussion

Remote sensing and field based ice velocity surveys determined that the only glacier with a stagnant terminus was Tahoma Glacier, with a mean velocity of 0.9 ± 1.4 cm d^{-1}. Other glaciers varied from low mean velocities of 2.1 ± 2.7 cm d^{-1} for North Mowich Glacier to a high mean velocity of 4.5 ± 1.3 cm d^{-1} for Carbon Glacier. The highest GPS measured velocities where on Carbon Glacier. Velocities reached 12.5 to 13.5 cm d^{-1} 1.2 to 1.5 km up glacier from the terminus.

Updated volume change estimates were significantly different than those made by Sisson et al (2011). Attempts to reproduce results from Sisson suggest a different method from ours was used for transforming the 1970 DEM from the NAD 1927 projection. Carbon Glacier lost the greatest ice volume (-88.8 10^6 m^3) while Emmons and South Tahoma glacier lost the least, -7.1 10^6 m^3 and -6.0 10^6 m^3, respectively. Puyallup Glacier had the greatest specific mass loss at -12.52 m with Carbon having the second greatest specific mass loss at -10.97 m. Emmons and Winthrop glaciers displayed ice thickening near their respective termini as a result of a terminal advance between 1970 and 2007/2008. As both glaciers seem to have advanced independently during the same time frame, it is likely that the advance is related to a kinematic wave, although a large rock fall event on Emmons Glacier has previously been suggested to be the cause of the advance.

Conclusion

The field based inventory found that minor adjustments needed to be made to the remote sensing inventories to bring them in line with where actual margins existed. Recent remote sensing based inventories were least consistent for the debris-covered terminus of Tahoma Glacier. Tahoma Glacier was also the only glacier where the terminus was determined to be stagnant. The other glaciers where surface velocity was measured were all determined to be active.

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