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Natural Resource Stewardship and Science

Mount Rainier National Park Glacier Mass Balance Monitoring Annual Report, Water Year 2009

North Coast and Cascades Network

Natural Resource Technical Report NPS/NCCN/NRTR—2011/484

ON THE COVER
Fall 2007 field work on Nisqually Glacier, Mount Rainier National Park
Photograph by: Mount Rainier National Park

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Contents

Figures

Tables

Page

Abstract

Glaciers are excellent indicators of climate change and important drivers of aquatic and terrestrial ecosystems. There are currently 27 major glaciers at Mount Rainier National Park, which cover about 90 km^2. Since 2003, we have monitored the seasonal mass balance changes of two of these glaciers, Emmons (11.6 km^2) and Nisqually (6.9 km^2), using six measurement points per glacier. The purpose of this report is to describe and summarize data collected during the 2009 water year.

Measurement of winter, summer, and net mass balance on Mount Rainier is complicated by steep (inaccessible) ice falls, debris cover, and a 2000m range in elevation. With the large vertical extent, glacial melt begins at the terminus in early April and above 3000 m in July. Maximum accumulation occurs between about 2000 and 2500 m elevation, with significant redistribution of snow by wind from southwest to northeast at higher elevations.

Winter snow accumulation reached a maximum depth of 5.2 ±0.4 m on Nisqually Glacier and 3.6 ±0.8 m on Emmons Glacier in water year 2009. Water equivalent (w.e.) values averaged across the entire glacier are near the 2003-2008 winter balance average on Nisqually Glacier (+2.2 m w.e.) and 65 percent of average on Emmons Glacier (+1.46 m w.e.).

Maximum summer melt reached -9.9 m at stake 4 on lower Emmons Glacier in late September. Net summer balance averaged across the measurement sites on Emmons Glacier was -3.79 ±0.75 m w.e., and -3.26 ±0.58 m w.e. on Nisqually Glacier. Significant debris cover on the lower portions of both glaciers slowed average ice melt to 65-80 percent of melt observed on adjacent stakes on clear glacier surfaces.

In 2009, annual net mass balance was negative for the seventh consecutive water year on Emmons Glacier (-1.8 ±0.75 m w.e.) and Nisqually Glacier (-1.64 ±0.58 m w.e.), which continued a long-term trend of declining volume for both glaciers. Since water year 2003, Emmons and Nisqually Glaciers have shown a cumulative net balance of -7.82 and -9.55 m w.e., respectively. Multiplying these two values by the area of each glacier provides an estimated glacial-loss by volume since 2003 of 91M m^3 at Emmons and 66 M m^3 at Nisqually. This represents an estimate volume loss of about 14 % and 31% at Emmons and Nisqually Glaciers.

We estimated that glaciers in the Nisqually and White River watersheds contributed 146 M m^3 (37.4 B gallons) of melt water between May 1 and September 30, comprising between 15-20 percent of the total runoff in these basins. This estimate includes snow, glacial ice, and firn.

Acknowledgments

Measurement of mass balance on four glaciers, adjustment of base maps, and administration of this project were only possible through the concerted effort of a large group of individuals. Field measurements were supported by Rebecca Lofgren, Benjamin Wright, Jeanna Wenger, Sharon Brady, Stefan Lofgren, Glenn Kessler and numerous Mount Rainer National Park climbing rangers. We would also like to recognize the peer-reviewers of this report, including Mark Huff, Rebecca Lofgren, Ashley Rawhouser, Regina Rochefort and Barbara Samora.

Introduction

The National Park Service began long-term monitoring of Nisqually and Emmons glaciers in Mount Rainier National Park (MORA) in 2003 (Figures 1-3). Monitoring includes direct field measurements of snow accumulation and melt at a sequence of stations placed at different elevations to estimate the mass balance of each glacier. Methods used here are directly comparable with those taken at four glaciers in North Cascades National Park Complex (NOCA) by the US National Park Service (NPS), at South Cascade Glacier by US Geological Survey, and globally. The purpose of this report is to describe and summarize data collected during the 2009 water year.

Glaciers are a defining feature of Mount Rainier National Park; as of 1994 there were 27 major glaciers on Mount Rainier with a combined area of 90 km^2 (35 mi^2) and numerous unnamed permanent snow or ice patches (Nylen 2002). The Emmons Glacier has the largest area (11.6 km^2; 4.3 mi^2) and Carbon Glacier has the lowest terminus altitude (1100 m; 3,600 feet) of all glaciers in the conterminous 48 states.

Glaciers are integral components of the region's hydrologic, ecologic, and geologic systems. Glacial melt water buffers the region's aquatic ecosystems from seasonal and interannual droughts. Aquatic ecosystems, endangered species such as salmon, bull trout and western cutthroat trout, and the hydroelectric and agricultural industries benefit from the seasonal and interannual stability glaciers impart to the region's hydrologic systems.

Glaciers significantly change the distribution of aquatic and terrestrial habitat through their advance and retreat. They directly influence aquatic habitat by the amount of cold, turbid melt water and fine-grained sediment they release. Glaciers also indirectly influence habitat through their effect on nutrient cycling and microclimate. Many of the subalpine and alpine plant communities in the park flourish on landforms and soils created by glaciers in the last century. Further, glaciers are habitat to a number of species, and are the sole habitat for ice worms (*Mesenchytraeus solifugus*) and certain species of springtails (Collembola) (Hartzell, 2003).

Glaciers are also sensitive and dramatic indicators of regional and global climate change. The total volume of all ice and snow on Mount Rainier was estimated to be 4.42 B m^3 (Driedger and Kennard 1986). Nylen (2002) estimated the area of glaciers had declined 27% between 1927and 1994.

The large volume of glaciers presents a significant geological hazard to park visitors and staff, and communities downstream of Mount Rainier. Glaciers are known to produce outburst floods, ice falls and other hazards regardless of volcanic activity, and can produce large volumes of water during larger eruptions (Scott et al. 1995). The most recent significant outburst flood occurred in 1947 on Kautz Creek, with smaller outburst floods on the Nisqually River in the 1940s and 1950s and Tahoma Creek in the 1990s. While monitoring for geologic hazards is not the focus of this program, incidental observations of changes in the mass, distribution, and surface condition of glaciers can provide important information to NPS personnel and the USGS Cascade Volcano Observatory.

The two index glaciers monitored represent varying characteristics of glaciers found in the North Cascades, including altitude, aspect, and geographic location. Established climbing routes allow for safe access without the need for helicopter support. The glaciers selected drain into two major watersheds (Nisqually and White rivers) from MORA and represent the entire altitude range of glaciers on the mountain. Both Nisqually and Emmons have excellent records of historic and prehistoric change (e.g. Harrison 1956, Heliker et al. 1983, Nylen 2002).

Four broad goals are identified to monitor glaciers as important Vital Signs of the ecological health of MORA:

1) Monitor change in area and mass of park index glaciers;
2) Relate glacier changes to status of aquatic and terrestrial ecosystems;
3) Link glacier observations to research on climate and ecosystem change; and
4) Share information on glaciers with the public and professionals.

Objectives identified to reach this program goal are:

- Collect a network of point surface mass balance measurements sufficient to define elevation versus balance relationships to estimate glacier averaged winter, summer and net balance for Emmons and Nisqually glaciers.
- Map and quantify surface elevation changes of Emmons and Nisqually glaciers every 10 years.
- Identify trends in glacier mass balance.
- Inventory margin position, area, condition, and equilibrium line altitudes of all park glaciers every 20 years.
- Monitor changes in surface features of glaciers, including ponds and ice falls.
- Monitor glacier melt, water discharge, and glacier area/volume change.
- Share data and information gathered in this program with a variety of audiences from school children to colleagues and the professional community.

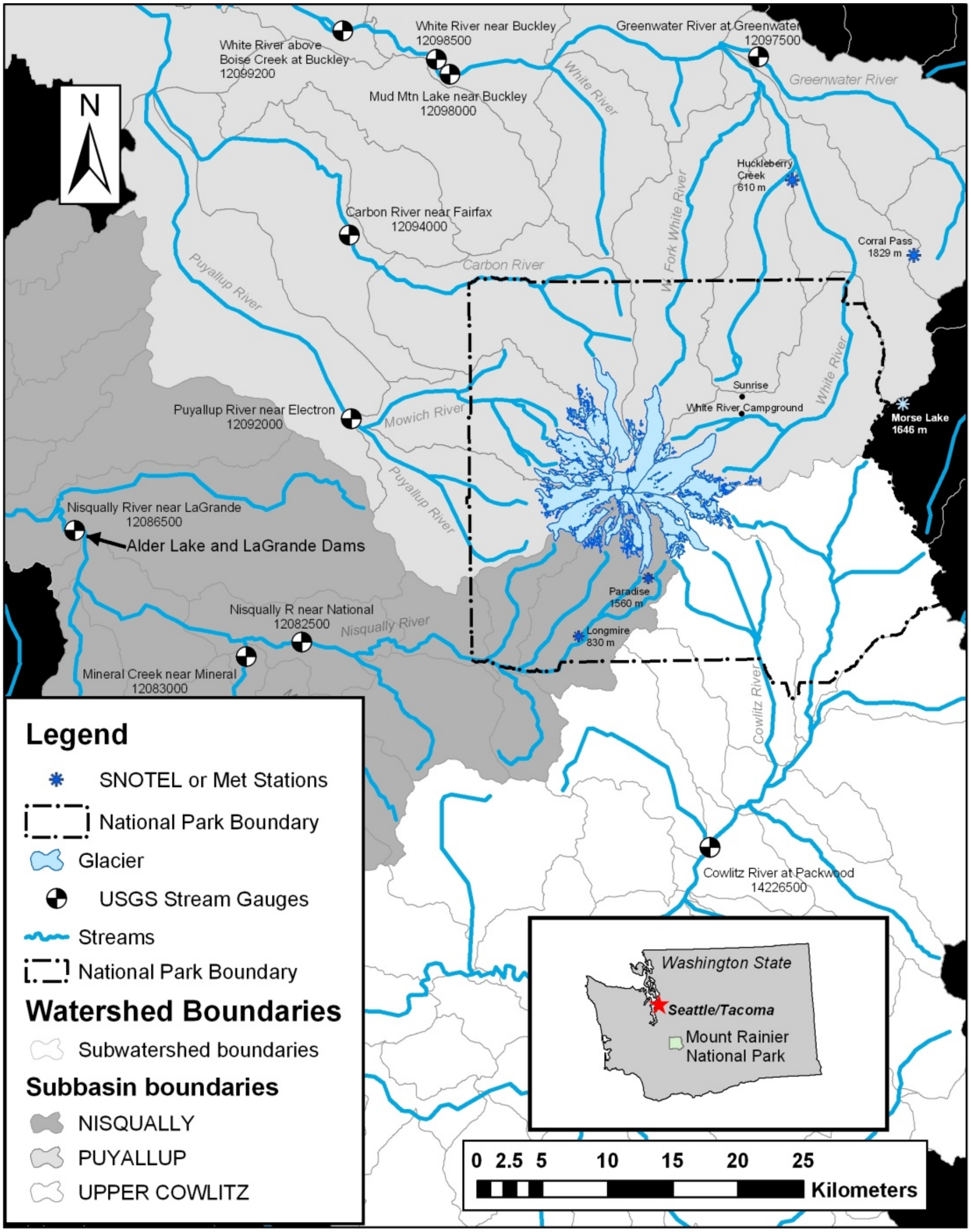

Figure 1. Locator map of Mount Rainier, major watersheds, streams, and USGS stream gauges. Weather stations are discussed in text.

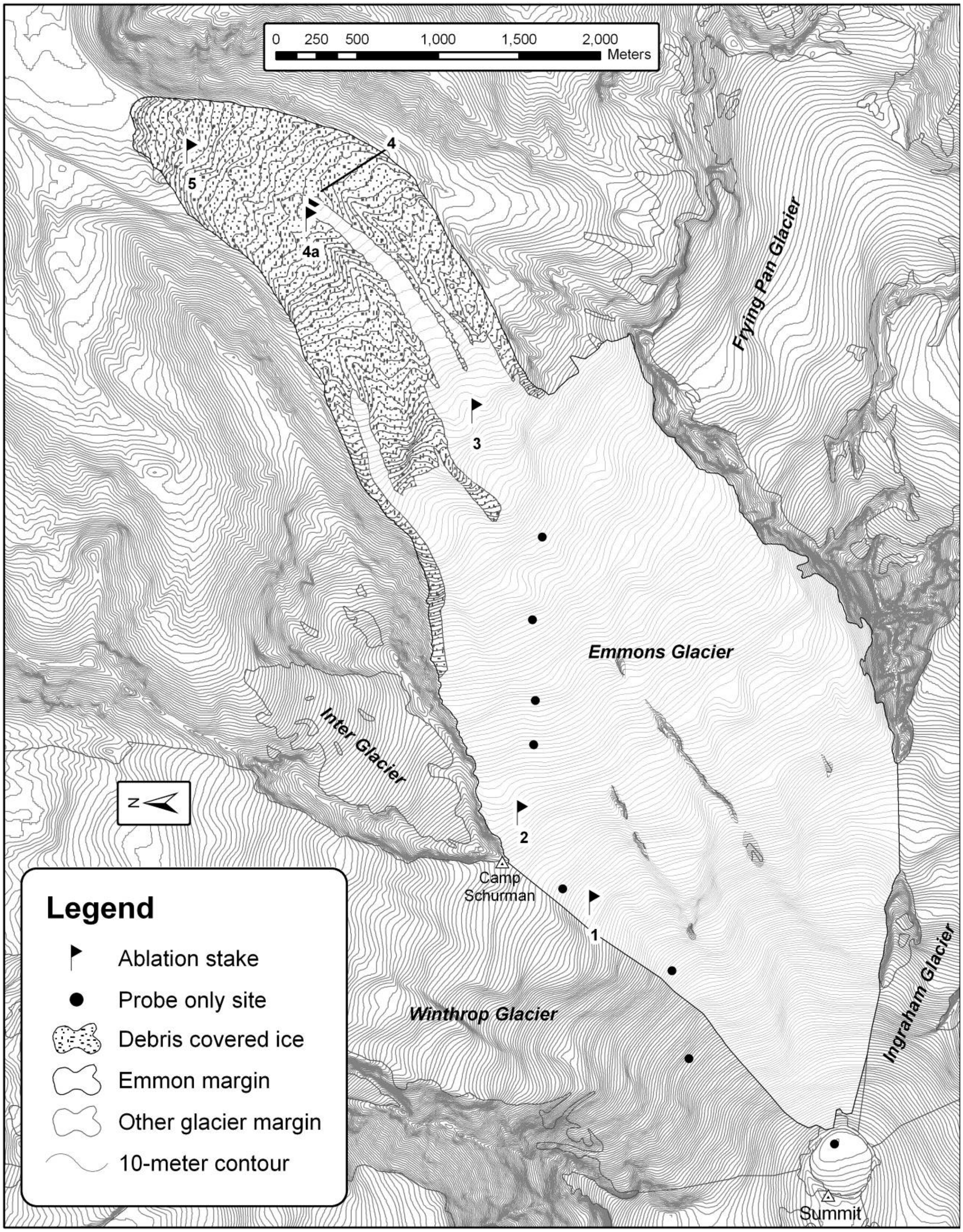

Figure 2. Emmons Glacier margin (1994), debris cover (2001), and measurement locations.

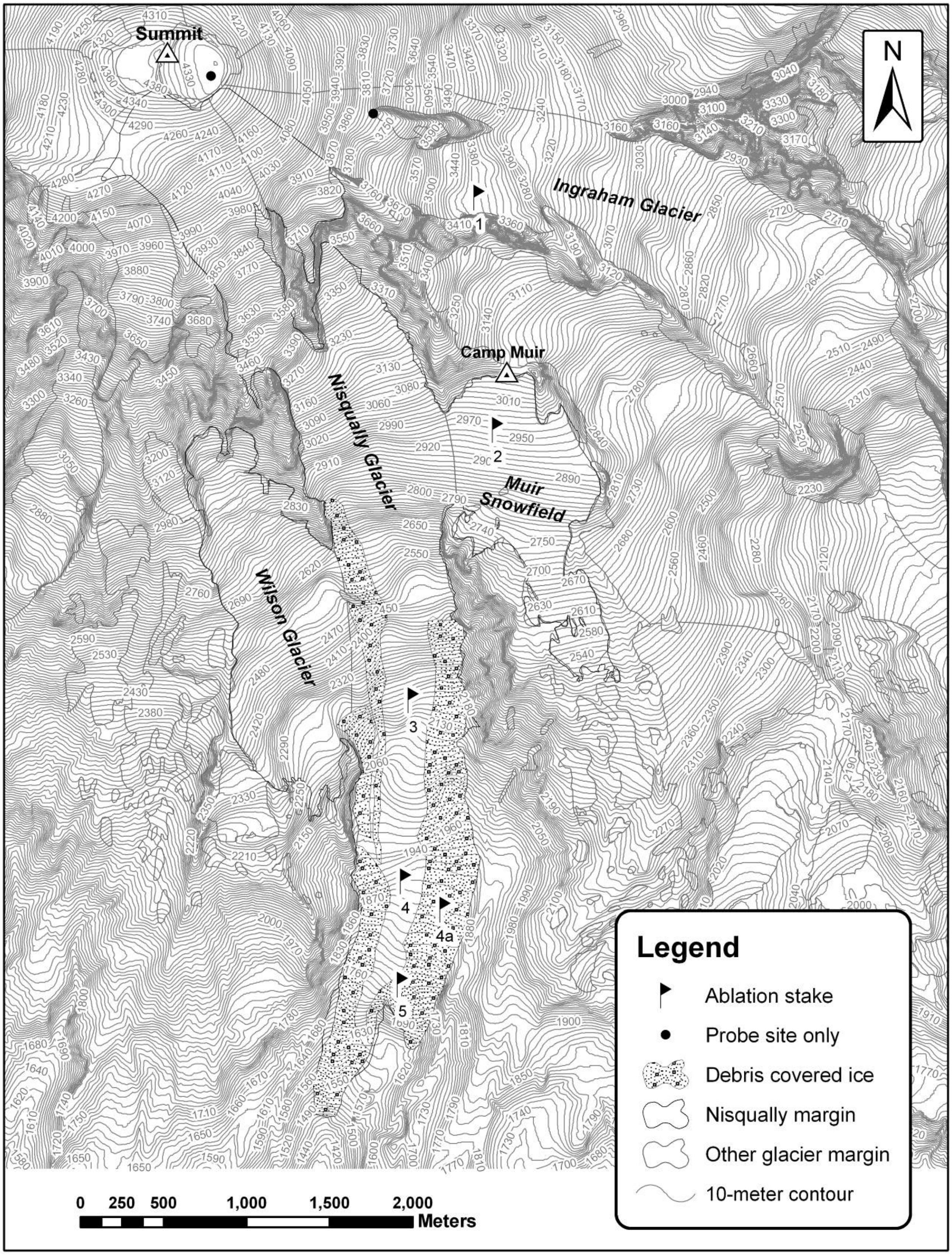

Figure 3. Nisqually Glacier margin (1994), debris cover (2001), and measurement locations.

Methods

Mass balance measurement methods used in this project follow the protocol developed by Riedel et al. (2010) which was modified from procedures used at NOCA since 1993 and published as a monitoring protocol by Riedel et al. (2008). Key studies that facilitated the development of these protocols were the 45 years of US Geological Survey (USGS) Water Resource Division research on the South Cascade Glacier in Mt. Baker-Snoqualmie National Forest by Meier (1961), Meier and Tangborn (1965), Meier et al. (1971), Tangborn et al. (1971), and Krimmel (1994-1996a, 1996b), and studies by Ostrem and Stanley (1969), Patterson (1981), and Ostrem and Brugman (1991). Data reduction methods in this report are modified from Ostrem and Brugman (1991) and Krimmel (1994-1999a, 1999b-2001), described in detail in Riedel et al. (2010), and incorporated into the measurement system summary provided below.

Measurement System

We use a two-season stratigraphic approach tailored to the conditions at Mount Rainier to calculate mass gained (winter balance) and mass lost (summer balance) on a seasonal basis (Riedel et al. 2010). Summation of these measurements allows for calculation of the net balance of a given glacier. The large altitude range of glaciers on Mount Rainier creates winter and summer seasons of dramatically different lengths at the terminus and the upper accumulation zone. Multiple spring, summer and fall visits are required to capture the maximum and minimum balances at different altitudes.

Winter balance is calculated from snow depth and bulk density measurements. Snow depth is measured at five to 10 points near six locations near the centerline of the glacier, resulting in 30-60 measurements per glacier. In years without reliable higher altitude data (above ~3400 meters), winter balance is assumed to follow the same pattern of decreasing winter accumulation above about 2200m observed during protocol development between 2002 and 2004. A minimum of two snow density measurements are taken in the spring on each glacier to determine the density versus altitude gradient.

Six ablation stakes are used to measure summer balance on each glacier, and are placed between late March and early June at locations from near the terminus to ~3400 meters altitude (Figures 2 and 3). For each glacier, two of the sites are located in areas with debris-covered ice, with the other stakes on debris-free ice. At a minimum, measurements of surface level change against the stakes are made in early summer thru early October. The change in level against the stake indicates the mass lost at the surface during the summer season (summer balance). Summer melting above the highest stakes is determined by extrapolating the melt versus elevation curve. The extended curve is constrained by the local measured temperature lapse rate determined by Longmire, Paradise, and Camp Muir weather stations, and allows us to determine the elevation of the zero summer balance altitude.

Terrestrial-based photographs are taken of each index glacier as a record of annual change of the terminus, relative surface elevation against bedrock, equilibrium line altitude, and snow, firn and ice coverage. These color photographs are taken during fall field visits at the same locations and of the same views of the glacier.

Glacial Meltwater Discharge

Glacier contribution to summer streamflow is calculated annually for Nisqually and White River watersheds. The summer season is defined as the period between May 1 and September 30. These dates approximately coincide with winter and summer balance field measurements and the beginning and end of the ablation season. Glacier contributions to summer streamflow are estimated using summer balance data versus altitude from Nisqually and Emmons glaciers and the area-altitude distributions of all glaciers in each watershed.

2003 to 2009 Record

In this report, we present data measured in 2009 and compared it to data collected from 2003-2008, using the methods described in Riedel et al. (2008, 2010). We present seven-year comparisons of winter, summer, net, and cumulative glacial balance, and summer glacial meltwater contributions to the White and Nisqually River watersheds.

Results

Measurement Error

Sources of error in mass balance measurements include variability in snow depth probes, incorrect measurement of stake height, snow density, and stake/probe position and altitude, and non-synchronous measurements with actual maximum and minimum balances. Errors are calculated on an annual, stake-by-stake, and glacier-by-glacier basis. Errors associated with winter, summer, and net balance estimates in water year 2009 on Nisqually Glacier were below average (Table 1). At Emmons Glacier, error estimates were near average values.

Table 1. Calculated error for Water Year 2009 mass balance on MORA glaciers (seven-year averages are in parenthesis).

	Average Error (m w.e.)		
Glacier	**Winter Balance**	**Summer Balance**	**Net Balance**
Emmons	±0.40 (0.45)	±0.63 (0.62)	±0.75 (0.77)
Nisqually	±0.20 (0.37)	±0.49 (0.86)	±0.58 (0.79)

Winter and Summer Balance

Winter snow accumulation reached a maximum depth of 5.2 ±0.4 m w.e. at 2175m elevation on upper Nisqually Glacier and 3.6 ±0.8 m w.e. at 2400 m elevation on Emmons Glacier (Figures 4 and 5). These approximate elevations are typically where the maximum winter accumulation is observed on these glaciers. Net winter balance (averaged across the glacier) in water year 2009 was 65 percent of average for Emmons Glacier at 1.46 ±0.4 m w.e., while Nisqually Glacier was near the long term average at +2.15 ±0.2 m w.e. (Figures 6 and 7).

Summer melt on lower stakes began in early-April and continued to early October. At upper stakes, summer melt season began in mid/late May and continued to mid-September. Summer balance at the lowest stakes without debris cover on Emmons Glacier was -9.9 m w.e. and -6.41 m w.e. on Nisqually Glacier.

Net summer mass balance was near average for Emmons Glacier (-3.79 ±0.63 m w.e.) and lower than average on Nisqually Glacier (-3.26 ± 0.49 m w.e.). Summer melt at debris covered stakes on the lower parts of both glaciers was below average, with values ranging from 63 to 80 percent of melt on debris-free parts of the glaciers (Figures 4-7). Based on extrapolated balance curves, there was a net gain of about 0.5 m w.e. on the summit of Mount Rainier.

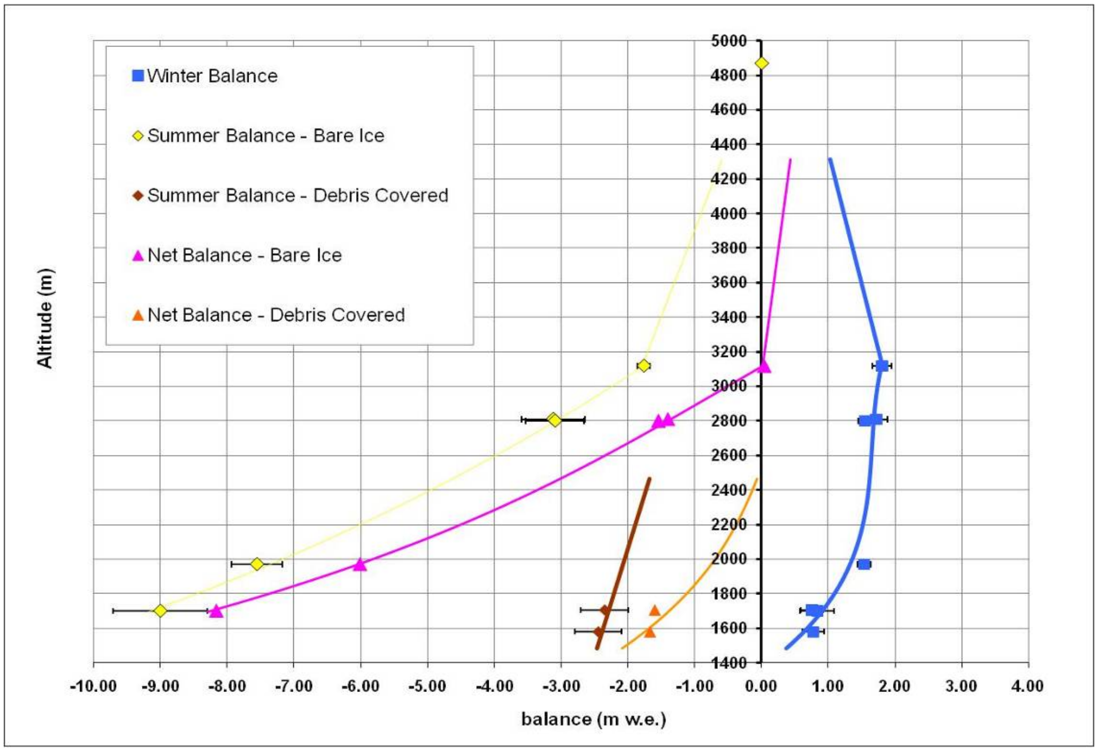

Figure 4. Emmons Glacier specific balance versus altitude, 2009.

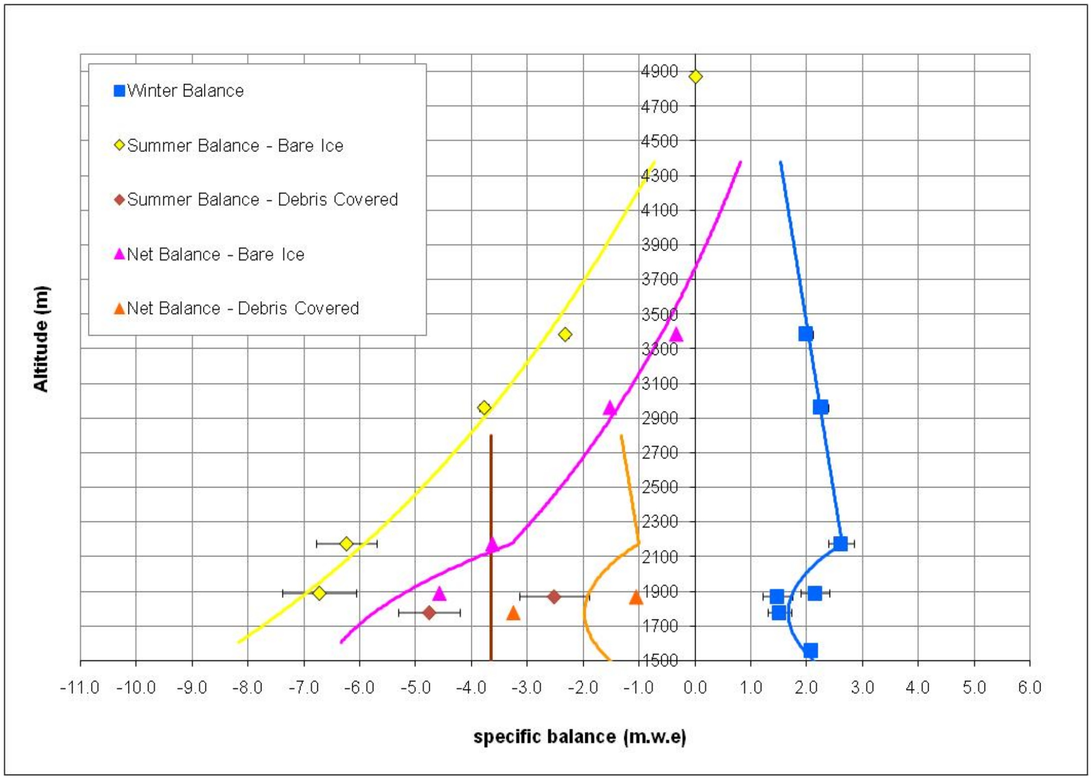

Figure 5. Nisqually Glacier specific balance versus altitude, 2009.

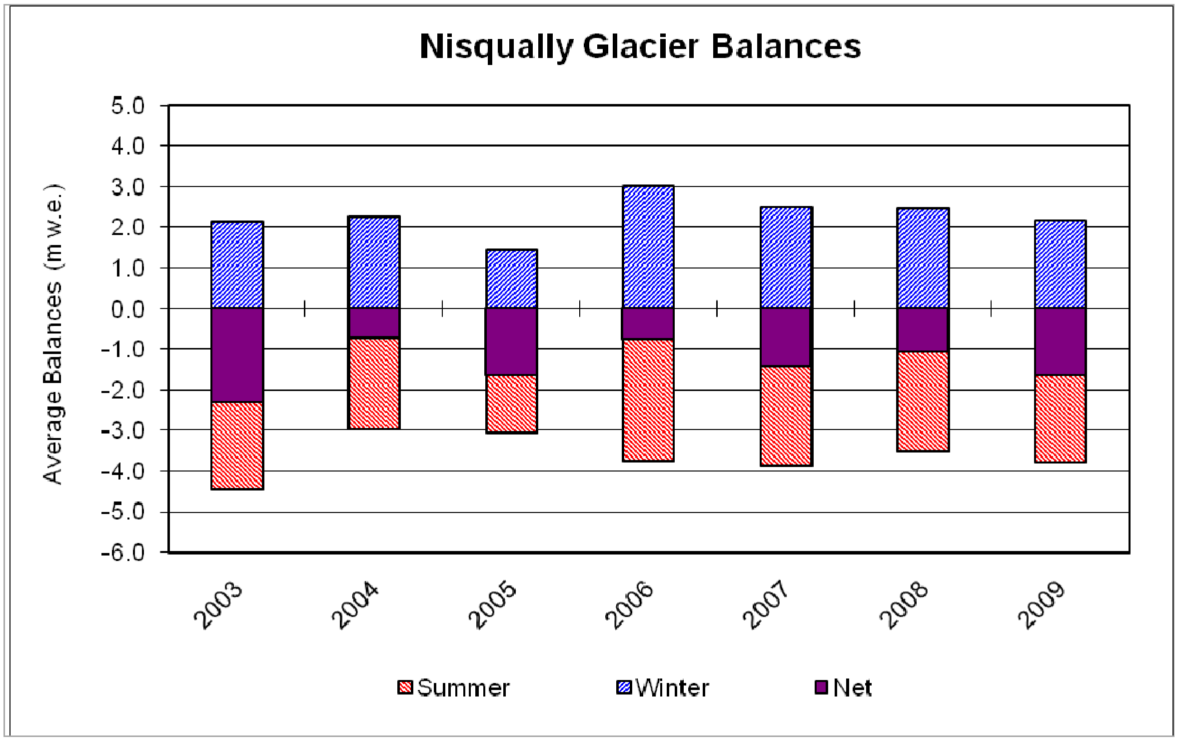

Figure 6. Winter, summer and net mass balances for Nisqually Glacier by water year.

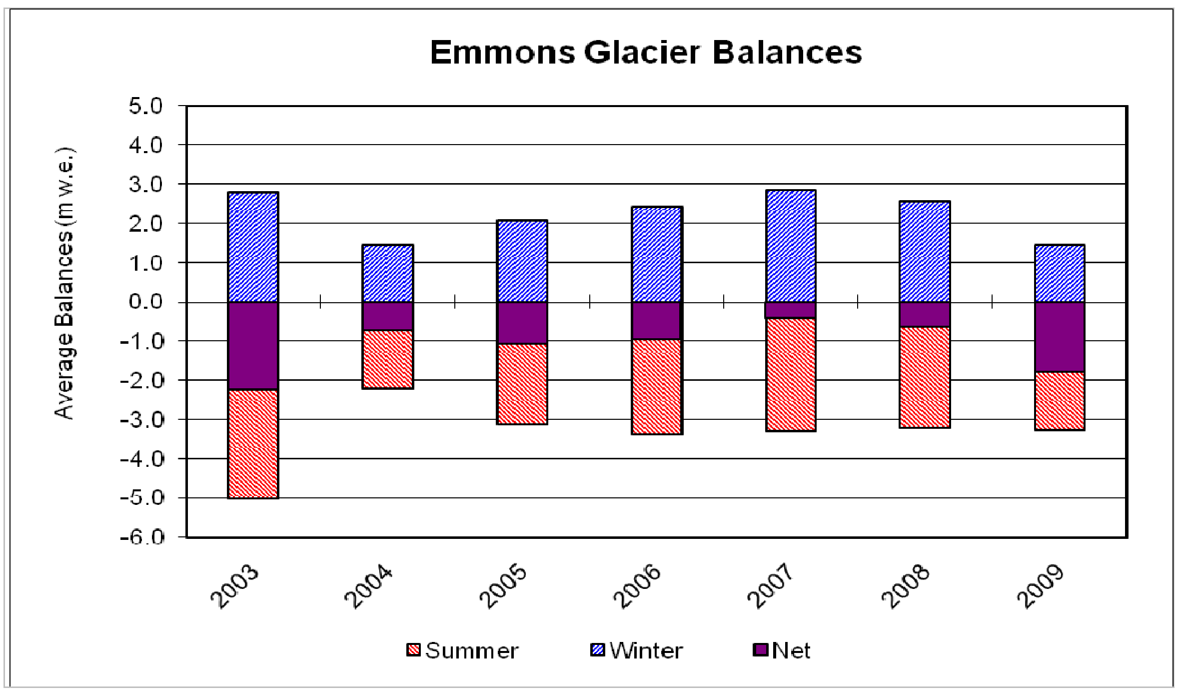

Figure 7. Winter, summer and net mass balances for Emmons Glacier by water year.

Net Balance

Annual net mass balances for Nisqually and Emmons glaciers were the second most negative since 2003, and these glaciers lost substantially more mass to melt than they accumulated in the previous winter (Figure 8). Emmons Glacier had a slightly larger negative net mass balance (-1.80 ±0.75 m w.e.) compared to Nisqually Glacier (-1.64 ±0.58 m w.e.). Even at 3000 m elevation camps Muir and Schurman, net mass balance in 2009 was about -1 m (Figures 4 and 5). Due to the large negative net mass balance, the combined volume loss from these two glaciers in water year 2009 was the second highest since monitoring began in 2003, and is estimated at -20.9 M m^3 for Emmons Glacier and -11.1 M m^3 for Nisqually Glacier.

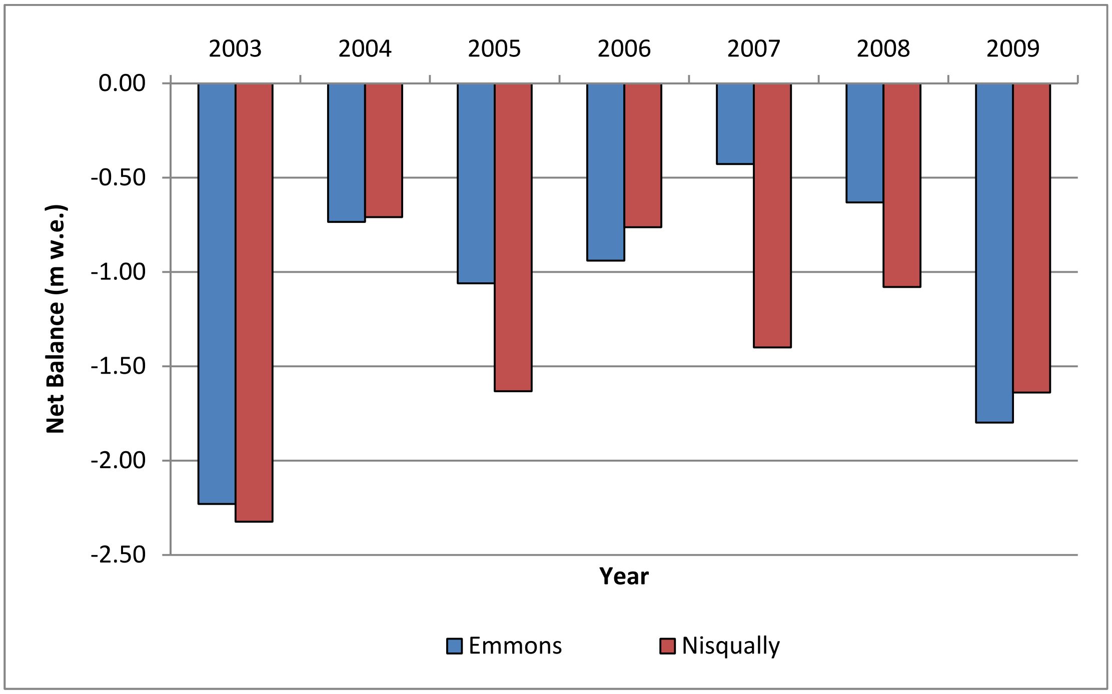

Figure 8. Net mass balance comparisons for each glacier by water year.

Cumulative Balance

Net mass balance for Emmons and Nisqually glaciers was negative in water year 2009 for the seventh consecutive year. This run of years where summer melt exceeds snowfall from the previous winter has led to a strongly negative trend in cumulative balance and a large loss in volume for both glaciers (Figure 9). Since 2003, the cumulative balance for Nisqually Glacier is -9.55 m w.e. and for Emmons Glacier it is -7.82 m w.e. The cumulative net volume loss in the past seven years is 90.7 M m^3 and 64.6 M m^3 for Emmons and Nisqually glaciers, respectively.

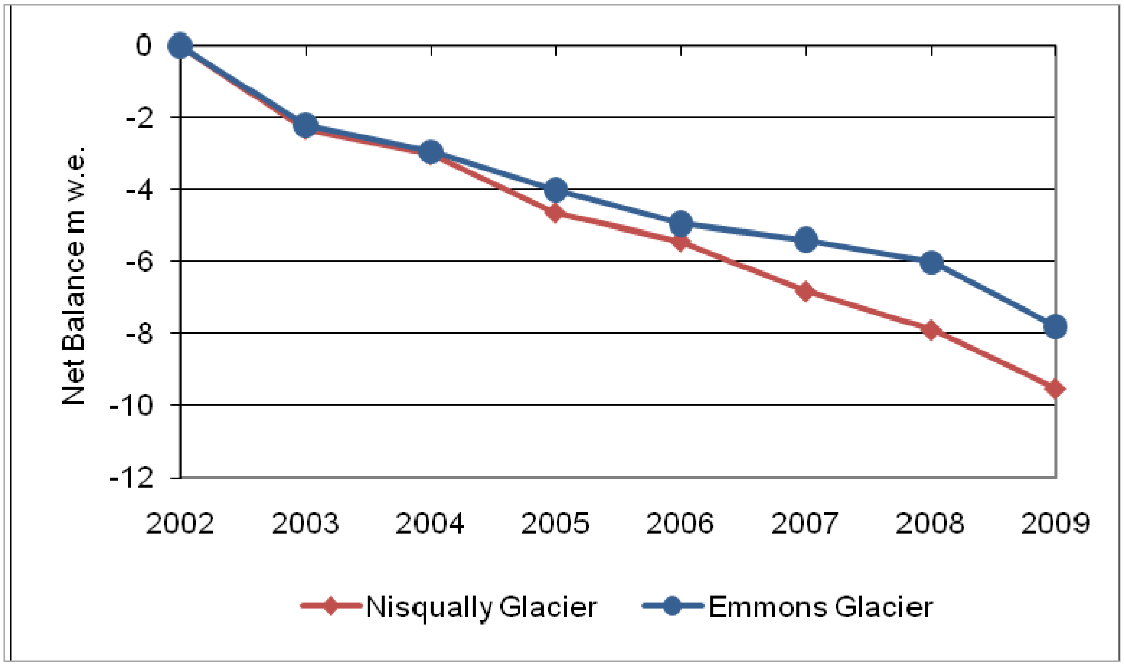

Figure 9. Cumulative balance for each glacier by water year.

Glacial Contribution to Streamflow

In White River basin at Buckley, glaciers contributed 85 M m^3 of water to streamflow between May 1 and September 30, representing about 15 percent of the total summer runoff (Table 2). Glaciers in the Nisqually basin above National contributed about 61M m^3 to streamflow, or 20 percent of the total summer runoff. Glacial contribution to summer runoff was slightly below average in both watersheds.

Since 2003, glaciers in the Whiter River Basin have annually contributed between 62.8-138.6 M m^3 of water to summer streamflow, representing about 11-26% of the total. Glaciers in the Nisqually basin have contributed between 46.7-68.6 M m^3 to summer streamflow, or about 13-33% of total runoff (Figure 10).

Table 2. Glacier contribution to summer streamflow for two MORA watersheds. Average, minimum and maximum values are for water years 2003-2009.

Site (% glacier area)	May-September Runoff (million cubic meters)				Percent Glacial Runoff to Total Summer Runoff			
	2009	**average**	**min**	**max**	**2009**	**average**	**min**	**max**
Nisqually Glacier	25.6	24.6	20.1	30.2				
Nisqually River Watershed (4.6)	60.9	57.2	46.7	68.6	20.1	22.0	13.3	33.1
Emmons Glacier	37.8	38.9	25.5	58.4				
White River Watershed (2.4)	85.3	92.3	62.8	138.6	15.2	17.5	10.8	25.8

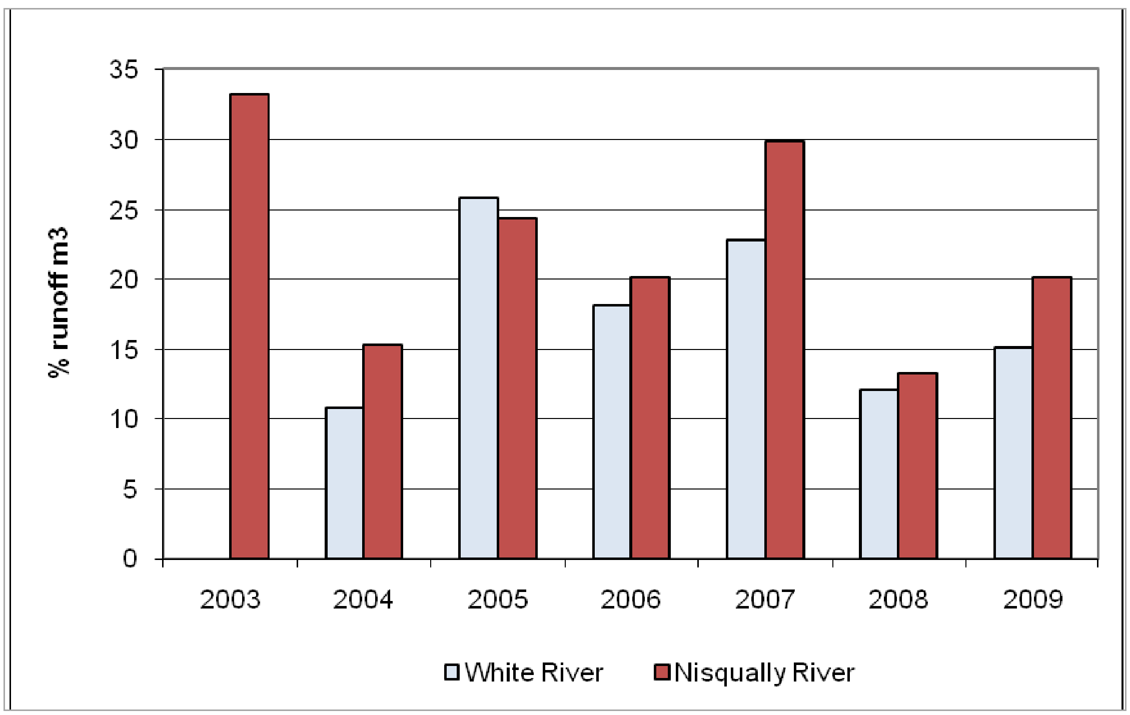

Figure 10. Total summer glacier meltwater contributions for two watersheds containing index glaciers.

Oblique Imagery

Oblique photographs are taken of each index glacier from permanent photo points as a record of change in area, surface elevation, equilibrium line altitude, and snow, firn and ice coverage. Photos from previous years are provided for comparison (Figures 11-14).

Figure 11. Emmons Glacier terminus, fall 2006. Photo was taken from moraine photo-point.

Figure 12. Emmons Glacier terminus, October 6, 2009. Photo was taken from moraine photo-point.

Figure 13. Nisqually Glacier, fall 2004. Photo was taken from Glacier Vista.

Figure 14. Nisqually Glacier, October 7, 2009. Photo was taken from Glacier Vista.

Discussion

Measurement error

Measurement error in estimating winter, summer, and net mass balance were about average on Emmons Glacier, and well below average on Nisqually Glacier (Table 1). Average net mass balance measurement error at Emmons is slightly higher than at Nisqually glacier, possibly because of more extensive debris cover on the lower glacier and more variable snow cover on the upper glacier.

Lower than average measurement error in water year 2009 is due in large part to strong development of a summer surface in the accumulation zone in 2008. This dense layer resulted in lower variability in probe measurements and smaller winter balance measurement error on both MORA glaciers.

Winter probe measurements are typically the primary source of error for winter balance estimates. Melt stake sinking and late season ablation are the main sources of summer balance error. At Mount Rainier it is also likely that there is significant internal melting caused by geothermal heat that is not measured. A thorough discussion of the sources of error is provided by Riedel et al. (2010).

Mass Balance

An important feature of the mass balance of the Mount Rainier glaciers is the influence of topography on snow accumulation. Lower Nisqually Glacier tends to have more accumulation of snow than lower Emmons due to its position on the wetter, windward side of Mount Rainier and location in a deep valley. Comparison of winter accumulation data from lower Nisqually Glacier with a SNOTEL[1] station at Paradise shows that the glacier collects wind-blown snow from ridges to the west, while wind strips some snow from the more exposed ridge SNOTEL site. Strong winds at higher elevation also re-distribute snow from upper Nisqually Glacier and the southwest side of the mountain to upper Emmons and Ingraham glaciers.

An interesting result from the winter balance measurements is the decrease in winter balance above about 3118 m on Emmons Glacier and 2200 m on Nisqually Glacier (Figures 4 and 5). The observed trend is also for the decrease in winter accumulation with altitude to be less severe on Emmons Glacier, probably because it receives wind-blown snow from the south side of the mountain. The consistent decrease in accumulation at higher elevations is likely due to the colder and drier conditions at altitude, as well topographic influences, and the significant redistribution of snow by high winds. Mass (2008) suggested that this point occurred at about 2100 m elevation

[1] SNOTEL stations provide real-time snow and climate data in the mountainous regions of the Western United States using automated remote sensing. The Natural Resource Conservation Service operates and maintains the Paradise SNOTEL station (http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=679&state=wa).

in Washington, and was a result of less mountain uplift of air and less moisture availability higher in the atmosphere.

Wind erosion and deposition of snow on the summit of Mount Rainier is significant, but to date has not been quantified. A LiDAR survey of the park in 2007 revealed the size of some of the wind shaped features such as scoured basins and drifts that cover large parts of the upper glacier (Robinson et al. 2010). A snow drift 8 m thick and several hundred meters wide consistently forms on upper Emmons Glacier south of Camp Schurman. Measurement of winter balance high on the mountain remains the most daunting challenge for mass balance monitoring, and more research is needed to determine how much snow falls and where it is redistributed by winds.

In summer, there is strong relationship between melting and elevation, which is the basis for estimating summer melt above the highest stakes, and glacial runoff. Rasmussen and Wenger (2009) used summer balance data from this study to evaluate a climate model relating summer glacier melt with positive-degree-day temperatures. In this paper melt measurements at the stakes were shown to correlate well with measurements compiled from regional upper air temperature models. This result corroborates our extrapolation of the summer melt curve to the summit using an air temperature lapse rate calculated from local weather stations.

Summer net mass balance is usually more negative on Nisqually Glacier due to its southern exposure. This relationship is particularly strong on the upper part of the glacier, which has less shade than the lower ice tongue below Glacier Vista.

Summer melt at debris covered stakes on the lower parts of both glaciers was appreciably less than melt at stakes in adjacent debris-free parts of the glaciers (Figures 4 and 5). On Nisqually Glacier, rock debris 15 cm thick slowed melt to about 80% of that on adjacent clean ice. On Emmons Glacier, beneath 25 cm of debris, melt was -2.4 m w.e. compared to -9 m w.e. at an adjacent stake without debris cover. This pattern is consistent with that observed in previous years, and underscores the importance of tracking debris covered ice melt separately. Further, if parts of lower Emmons and Nisqually glaciers have an increase in debris cover extent or thickness, the rate of melting may slow on the lower parts of both glaciers.

Equilibrium line altitudes (ELA) for Nisqually and Emmons glaciers in water year 2009 were 3730 m and 3110 m elevation, respectively. Emmons ELA in 2009 is nearly 1000 m above the 2003-2009 average ELA, while the 2009 ELA at Nisqually Glacier was slightly below the seven-year average (3164 m). The unusually high ELA in water year 2009 on Emmons Glacier was due primarily to the low winter balance, and this glacier's sensitivity to accumulation is not surprising given its location on the dry (rain-shadow) side of Mount Rainier.

Cumulative Balance

Water year 2009 represented the seventh consecutive year of negative net mass balance for Emmons and Nisqually Glaciers. The cumulative run of years with negative net mass balance indicates a strongly negative trend in cumulative balance and a large loss in volume for both glaciers (Figure 9). Since 2003, the cumulative net mass balance for Nisqually Glacier is -9.6 m w.e. and for Emmons Glacier it is -7.8 m w.e.

This trend and magnitude of ice loss are similar to other mountain glaciers in the region and across the globe. Cumulative net mass balance at four glaciers at North Cascades National Park during the same period range from-7.5 to -9 m. Global mean loss of glacial ice between 1996-2005 is about -5.8 m (Zemp and Woerden 2008). Global mean values are lower than for temperate mountain glaciers in Washington State. North American mountain glaciers had cumulative balances that ranged from -6.5 m (Blue Glacier) to -13.8 m (Ice Worm Glacier) between 1985-2005 (Zemp and Woerden 2008).

Seemingly, the large size and high elevation of Mount Rainier's glaciers would result in net balances that were more positive than smaller glaciers in the Cascades. However, cumulative balance at MORA in the past seven years is comparable to that measured at NOCA over the same period. Exposure of the upper parts of most glaciers to the sun on Mount Rainier is greater than for most other mountain glaciers in the Cascades. Further, wind erosion and deposition of snow and the steep, narrowly shaped accumulation zones on Cascade volcanoes are important mass balance factors.

The lowest cumulative net mass balance since 2003 at individual stakes are -35.6 m at stake 5 on Nisqually Glacier at 1765 m elevation, and -60 m at stake 4 on Emmons Glacier at 1714 m. Lower elevation stakes at Emmons have substantial debris cover, which increased the cumulative balance since 2003 to -24 m. From these data it is clear that most glacial volume loss is between 1700-3000m, above the main debris cover on both glaciers.

Glacial Contribution to Streamflow

Substantial melt of Emmons and Nisqually glaciers since 2003 underscores the importance of glaciers to major river systems heading on Mount Rainier. Glaciers in the Nisqually and White River basins contributed 15 and 20% respectively to summer streamflow at the National and Buckley gage sites in water year 2009. The volume of glacial runoff in these valleys was substantial at 60.9 M m^3 (15.6 B gallons) to White River and 85.3 M m^3 (21.8 B gallons) to Nisqually River.

Negative net mass balance led to an average glacial contribution to summer runoff in water year 2009 that is within the range of values observed since 2003 (Figure 10). Variability in glacial contribution to runoff represents annual net storage or loss to the glaciers in that basin. During water years with wet winters and cool, cloudy summers, the relative amount of the glacial contribution decreases as snow fall is stored through the summer on the glaciers, and less ice and firn melt (i.e. 2004 and 2008). In these water years, the percent of glacial contribution to total summer runoff also declines because heavy snowfall across the watersheds drowns-out the glacial contribution. The largest summer runoff from glaciers occurred in water year 2003, when hot, dry weather melted about 140 M m^3 (36 B gallons) of snow, ice and firn that flowed into the White River.

Glacial runoff estimates represent melt from ice, firn and snow on the glacier surface between about early April to later September. Measurement of the firn and ice-only component of the melt was not made due to the time-transgressive start of the melt season on glaciers spanning 2400 m in elevation, debris cover, and variable depth of snow.

Glaciers in the White River drainage contribute nearly twice the volume of melt water as do those in the Nisqually basin. This is due primarily to more extensive glacial cover in the White River basin (25.6 km^2 vs. 15.6 km^2) even though the ratio of glacial area to watershed area is twice as high in the Nisqually Basin. This underscores the importance of glaciers in the more arid White River valley, where snowfall is lower, and also reflects a similar pattern observed at North Cascades National Park.

There are two important dimensions to rapid decline of glaciers at Mount Rainier. At a seasonal timescale, warmer summers increase the rate of melt. This trend is offset to some extent by the longer timescale reduction in glacier area and volume. Thus while glaciers are delivering more water due to higher melt rates, their storage capacity is being diminished.

While the area of glaciers at MORA had decreased 27% between 1913 and 1994 (Nylen 2002), areal changes may not be the primary mode of glacial recession. Instead, rapid surface melting and stagnation of the lower parts of glaciers may be a more common pattern, as indicated by the rapid loss in volume of glaciers at Mount Rainier. Multiplication of cumulative net mass balance by the area of each glacier results in an estimate of total volume loss since 2003 at Emmons Glacier of 91 M m^3, and 66 M m^3 of Nisqually Glacier. Given volume estimates for these glaciers (Drieger and Kennard 1986), this represents a volume loss of about 14% on Emmons Glacier and 31% at Nisqually Glacier. This estimate is likely somewhat high on Nisqually Glacier due to more negative summer balance and less positive winter balance on Muir Snowfield, where measurements are taken, than mid-Nisqually Glacier, which is inaccessible due to a steep ice fall. These estimates of volume could also be high because surface mass balance tends to underestimate winter balance. This is a particular problem on the upper surfaces of glaciers at high elevations on Mt. Rainier, where lack of development of a dense summer surface leads to increased probe error. Drieger and Kennard estimates of ice volume on these glaciers may also be low.

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