National Park Service
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Natural Resource Stewardship and Science

Mount Rainier National Park Glacier Mass Balance Monitoring Annual Report, Water Year 2011

North Coast and Cascades Network

Natural Resource Data Series NPS/NCCN/NRDS—2015/752

ON THE COVER

August 2011 field work on lower Nisqually Glacier, Mount Rainier National Park. Debris from a large rock avalanche, that occurred on the upper Nisqually Glacier, can be seen in the upper right of the photo.

Photograph by: Mount Rainier National Park

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Data Series is intended for the timely release of basic data sets and data summaries. Care has been taken to assure accuracy of raw data values, but a thorough analysis and interpretation of the data has not been completed. Consequently, the initial analyses of data in this report are provisional and subject to change.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data. Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

This report is available from The North Coast and Cascades Network (http://science.nature.nps.gov/im/units/nccn/reportpubs.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

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Abstract

Glaciers are sensitive indicators of climate change and important drivers of aquatic and terrestrial ecosystems. Glaciers are a high-priority Vital Sign in the North Coast and Cascades Network (NCCN) monitoring plan (Riedel et al. 2008). 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 methods developed as part of the NCCN protocol for *Long Term Monitoring of Glaciers at Mount Rainier National Park* (Riedel et al., 2010). The purpose of this report is to describe and summarize data collected during the 2011 water year.

Measurement of winter, summer, and net mass balance on Mount Rainier is complicated by steep, often inaccessible ice falls, debris cover, and a 2000 m range in elevation. With the large vertical extent, glacial melt typically begins at the terminus in April and does not begin above 3000 m until 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.

In water year 2011, winter snow accumulation reached a maximum depth of 3.48 m w.e. on Nisqually Glacier and 3.20 m w.e. on Emmons Glacier. Water equivalent (w.e.) values averaged across the entire glacier were 138% of the 2003-2010 average on Nisqually Glacier [+3.28 (±0.77) m w.e.] and 104% of average on Emmons Glacier [+2.35 (±0.46) m w.e.].

Net summer balance on Nisqually Glacier was -2.84 (±1.00) m w.e., and -2.37 (±0.72) m w.e. on Emmons Glacier (81 and 73% of average, respectively). Significant debris cover on the lower portions of both glaciers slowed average ice melt to 41-80% of melt observed on adjacent stakes on clear glacier surfaces.

In 2011, annual net mass balance was positive for Nisqually Glacier [+0.44 (±1.26) m w.e.], the second consecutive positive year. Emmons Glacier had a slight negative balance [-0.02 (±0.85) m w.e.]. Net balances for both glaciers were within the margin of error. Despite the modest increases in glacier balance since 2010, the overall trend in cumulative balance has been strongly negative for both glaciers. Since 2003, the cumulative balance for Nisqually Glacier is -8.61 m w.e. and for Emmons Glacier it is -7.71 m w.e. The cumulative net volume loss in the past eight years is 89.4 million m^3 and 58.1 million m^3 for Emmons and Nisqually glaciers, respectively.

The equilibrium line altitude was 150 m below average on Emmons Glacier and more than 500 m below average on Nisqually Glacier. The large departure from average for Nisqually glacier was attributed in part to significant snow avalanche debris originating from the upper mountain being deposited at stakes 4 and 4A. This resulted in the deepest snow measured on either glacier in 2011 and the deepest snow measured at these sites in the last 9 years.

Acknowledgments

Measurement of mass balance on two 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, Steven Dorsch, Sharon Brady, Stefan Lofgren, Glenn Kessler and numerous Mount Rainer National Park climbing rangers.

Glossary

Ablation: All processes that remove mass from a glacier such as melting, runoff, evaporation, sublimation, calving and wind erosion.

Accumulation: All processes that add mass to the glacier such as snowfall, wind drifting, avalanching, rime ice buildup, rainfall, superimposed ice and internal accumulation

Equilibrium Line altitude (ELA): The altitude where annual accumulation and ablation are equal and net balance is zero. The ELA is determined by the either the altitude of the snow or firn line in the fall or from fitting a curve to point mass balance data, termed balanced-budget ELA.

Firn: A metamorphosed material between snow and ice. Snow becomes higher density firn after existing through one summer melt season but having not yet metamorphosed into glacier ice.

Mass balance: The change in mass of a glacier measured between two points in time.

Net mass balance: The sum of winter balance (which is positive) and summer balance (which is negative), or two successive minimums. Net mass balance is positive if the glacier is gaining mass and negative if it is losing mass.

Point mass balance: The balance (winter, summer or net) at an individual site (i.e. ablation stake).

Summer mass balance: The loss of snow, firn, and ice from ablation (mostly melting).

Water equivalent (w.e.): A measure of the amount of water contained in snow, firn and ice. Balance values are expressed in water equivalent due to the varying densities of water, snow, firn and ice, thus allowing for a single normalized value to be used.

Winter mass balance: The gain of a winter season snowfall, wind drifting, avalanching, rime ice buildup, rainfall, superimposed ice and internal accumulation.

Water year (WY): The Water Year (or Hydrologic Year) is most often defined as the period from October 1st to September 30 of the following year. It is called by the calendar year in which it ends. Thus, Water Year 2011 is the 12-month period beginning October 1, 2010 and ending September 30, 2011. The period is chosen so as to encompass a full cycle of winter accumulation and melt.

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 (USGS), and globally. The purpose of this report is to describe and summarize data collected during the 2011 water year.

Glaciers are a defining feature of MORA; 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. The total volume of all ice and snow on Mount Rainier was estimated to be 4.42 billion m^3 (Driedger and Kennard 1986).

Glaciers are integral components of the region’s hydrologic, ecologic, and geologic systems. Delivery of 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 themselves provide habitat for a number of species, and are the sole habitat for ice worms (*Mesenchytraeus solifugus*) and certain species of springtails anthropods (*Collembola*; Hartzell, 2003).

Glaciers are also sensitive and dramatic indicators of regional and global climate change. Glaciers provide valuable insight to climate change over longer time periods than most other climate measures (Paterson, 1981). Nylen (2002) estimated the area of glaciers had declined 27% between 1927 and 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, Tahoma Creek in the 1990s and Van Trump Creek in 2006. 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 glaciers selected to monitor drain into two major watersheds (Nisqually and White rivers) from MORA and represent the entire altitude range of glaciers on the mountain (Figure 1). By selecting these glaciers it allows us to monitor aspect-related extremes in climate and glacier change, with Emmons on the northeast side of the mountain and Nisqually on the southwest side. Established climbing routes allow for safe access without the need for helicopter support. 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 frame our glacier monitoring:

1. Monitor the change in area and mass of park index glaciers;
2. Relate glacier changes to the 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 for achieving the program goals are:

- Collect a network of surface mass balance measurements sufficient 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.

2003 to 2011 Record

In this report, we present data measured in 2011 and compared them to data collected from 2003-2010 using the methods described in Riedel et al. (2008, 2010). We present nine-year comparisons of winter, summer, net, and cumulative glacial balance, and summer glacial meltwater contributions to the White and Nisqually River watersheds.

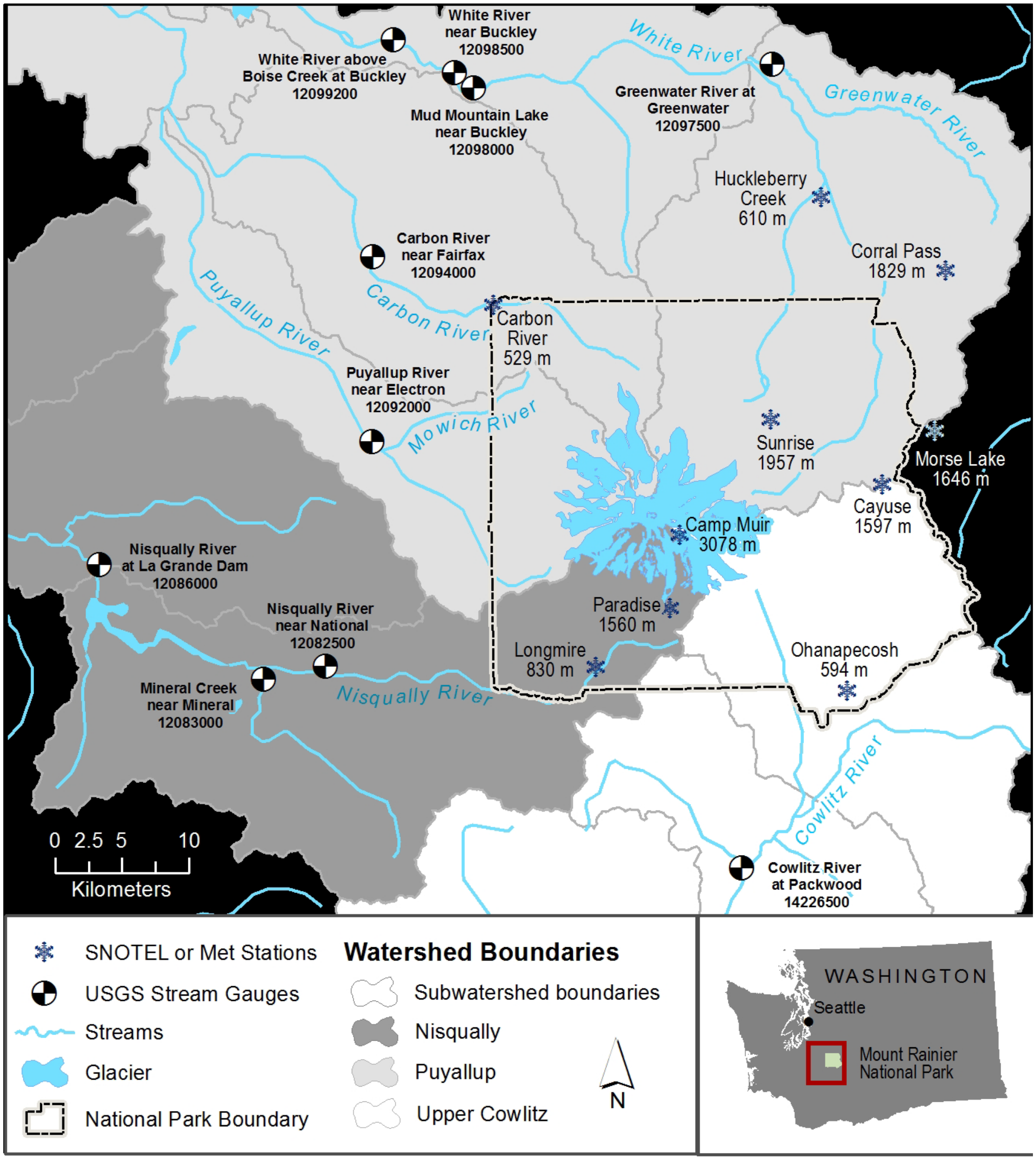

Figure 1. Map of Mount Rainier National Park and nearby surrounding area, with major watersheds, streams, USGS stream gauges, and weather stations identified.

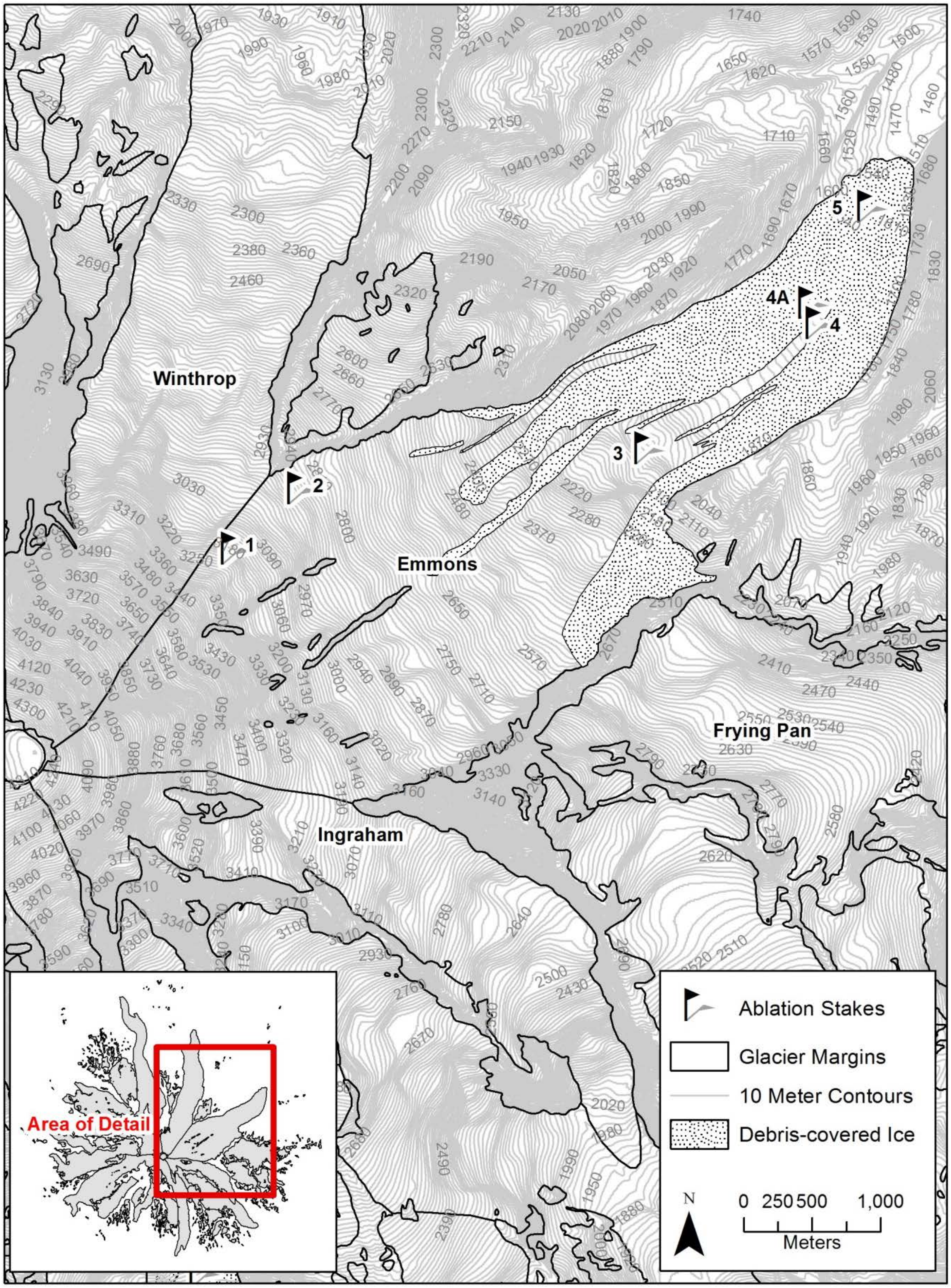

Figure 2. Emmons Glacier margin (1994), debris cover (2001), and measurement locations.

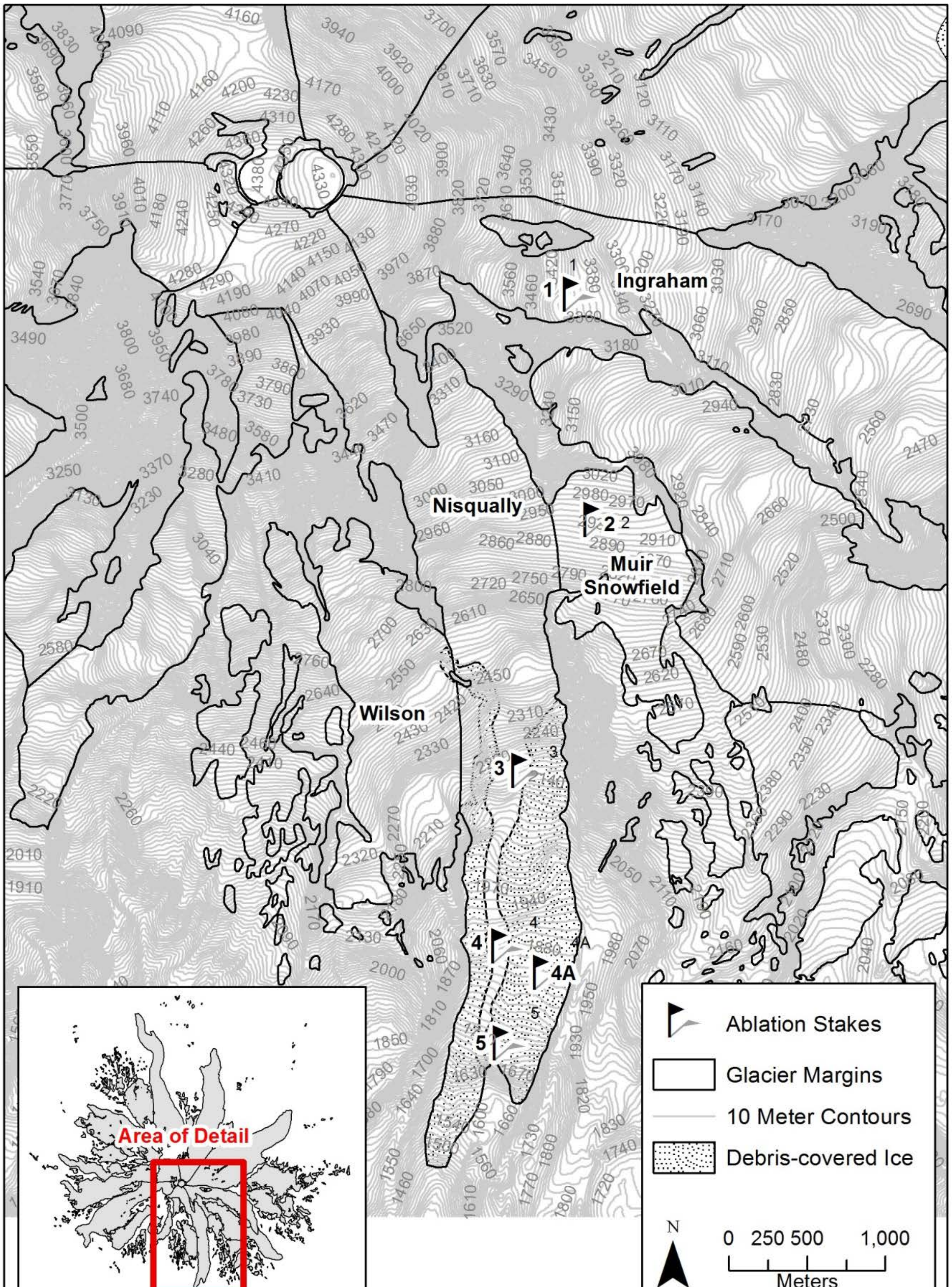

Figure 1. Nisqually Glacier margin (1994), debris cover (2001), and measurement locations.

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 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 other studies by Østrem and Stanley (1969), Paterson (1981), and Østrem and Brugman (1991). Data reduction methods in this report are modified from Østrem 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 glacial 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 2200 m 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. The stakes 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 stakes are located in areas with debris-covered ice, with the remaining four stakes located on debris-free ice. At a minimum, measurements of surface level change against the stakes are made twice annually, in early summer and in early fall. 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 (Figure 1), 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.

Provisional Data

Accurate glacier maps are an important component of this monitoring program. Point measurements are extrapolated for the entire glacier using area and altitude data taken from base maps. The two index glaciers are remapped on a 10-year cycle. The updated reference maps are used for mass balance calculations until the next reference maps are created; they are also used to back-adjust mass balance calculation for five previous years, or the mid-point between the current map and the map from previous cycle. As a result, mass balance data remains provisional until the next mapping cycle is completed and all pertinent mass balance calculations have been back-adjusted.

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 in mass balance 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 (WY) 2011 on Nisqually Glacier were above average (Table 1). The large departure from normal was attributed to highly variably probe measurements at both stakes 3 (2175 m) and 4a (1870 m), which were located in snow avalanche deposits. At Emmons Glacier, error estimates were near average values.

Table 1. Calculated error for Water Year 2011 mass balance calculations for MORA index glaciers, period of record averages in parenthesis.

	Average Error (m w.e.)		
Glacier	**Winter Balance**	**Summer Balance**	**Net Balance**
Emmons	±0.46 (0.45)	±0.72 (0.68)	±0.85 (0.82)
Nisqually	±0.77 (0.37)	±1.00 (0.82)	±1.26 (0.79)

Winter and Summer Balance

Winter balance (averaged across the glacier) in WY2011 was 104% of average for Emmons Glacier at +2.35 (±0.46) m w.e.; and 138% of average for Nisqually Glacier at +3.28 (±0.77) m w.e. (Figures 4 and 5). A cool and wet spring resulted in winter accumulation continuing into early May at lower elevation stakes and late May at upper elevation stakes. The elevation of maximum snow accumulation on Emmons Glacier was near the 9-year average at 3.20 m w.e. at 3065 m (Figure 6). Significant snow avalanche debris originating from the upper mountain was deposited at stakes 4 and 4A on Nisqually Glacier resulting in the deepest snow measured on either glacier and the deepest snow measured at these sites in the last 9 years (Figure 7).

Summer mass balance was 73% of average for Emmons Glacier [-2.37 (±0.72) m w.e.] and 81% of average for Nisqually Glacier [-2.84 (± 1.00) m w.e.]. Summer melt generally decreases with increases in elevation; most melt occurs at the lowest non-debris-covered stakes. On Emmons Glacier at 1700 m, the summer mass balance was -5.75 (±1.18) m w.e. and on Nisqually Glacier at 1890 m is was -4.41 (±0.45) m w.e.

Summer melt at debris-covered stakes on the lower parts of both glaciers was also below average (Figures 6 and 7). Melt at debris-covered ice sites is typically lower than similar debris-free sites, a result of the insulating properties of the debris. On Emmons Glacier, total melt at debris-covered ice sites was 41% of melt on adjacent debris-free sites. On Nisqually Glacier, the winter snowpack never completely melted at debris-covered sites, as a result the ratio of melt was 80% when compared to similar debris-free sites.

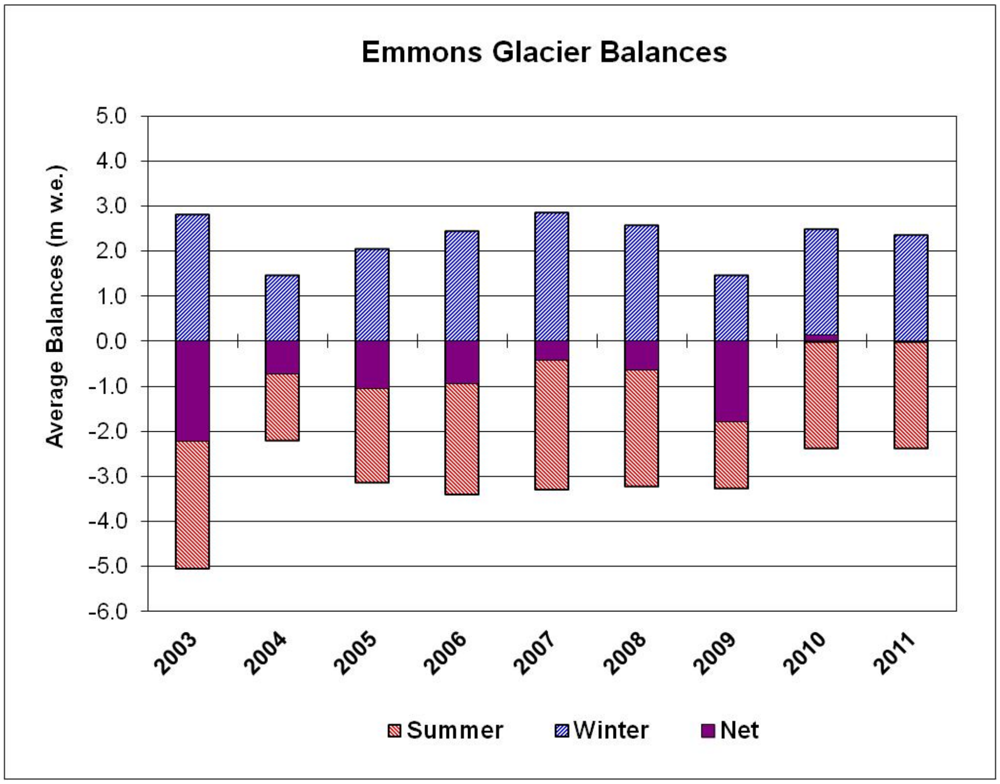

Figure 4. Winter, summer and net mass balances for Emmons Glacier by water year.

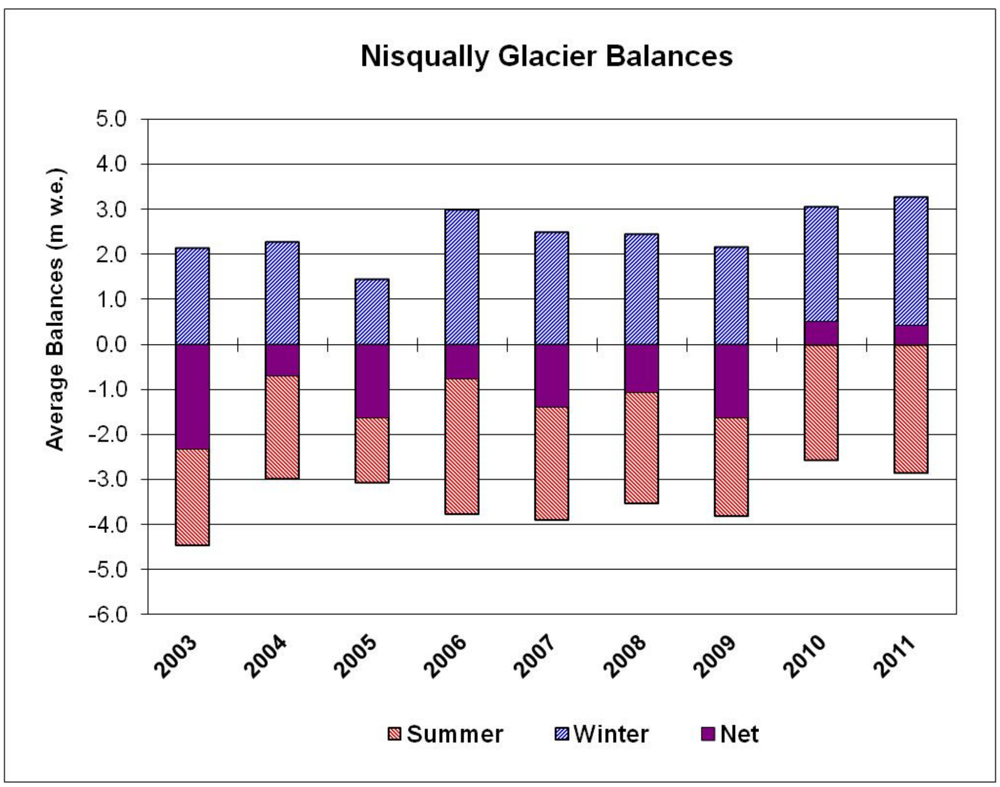

Figure 5. Winter, summer and net mass balances for Nisqually Glacier by water year.

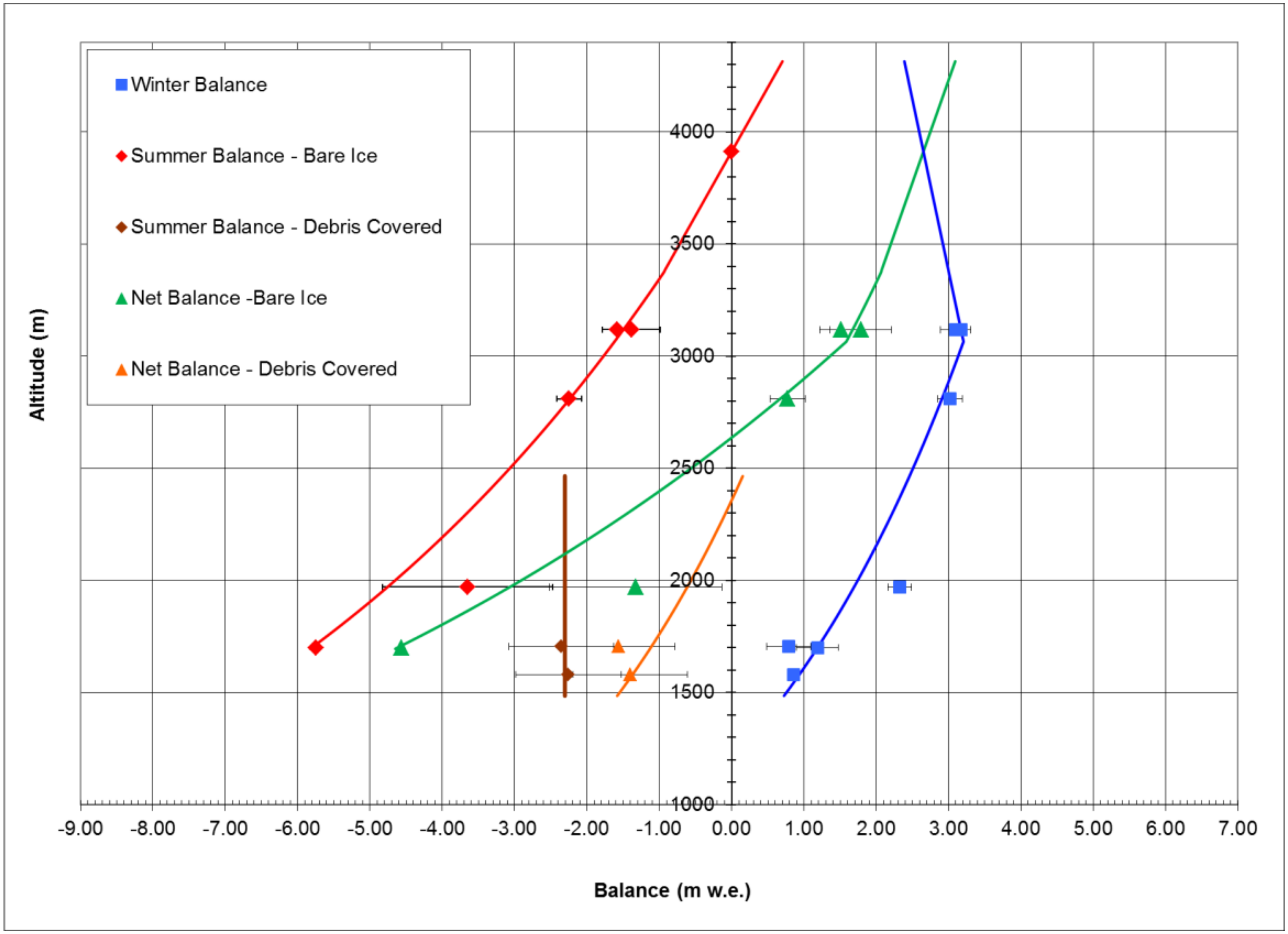

Figure 6. Estimated summer, winter, and net balance measured at varying altitudes on Emmons Glacier in 2011.

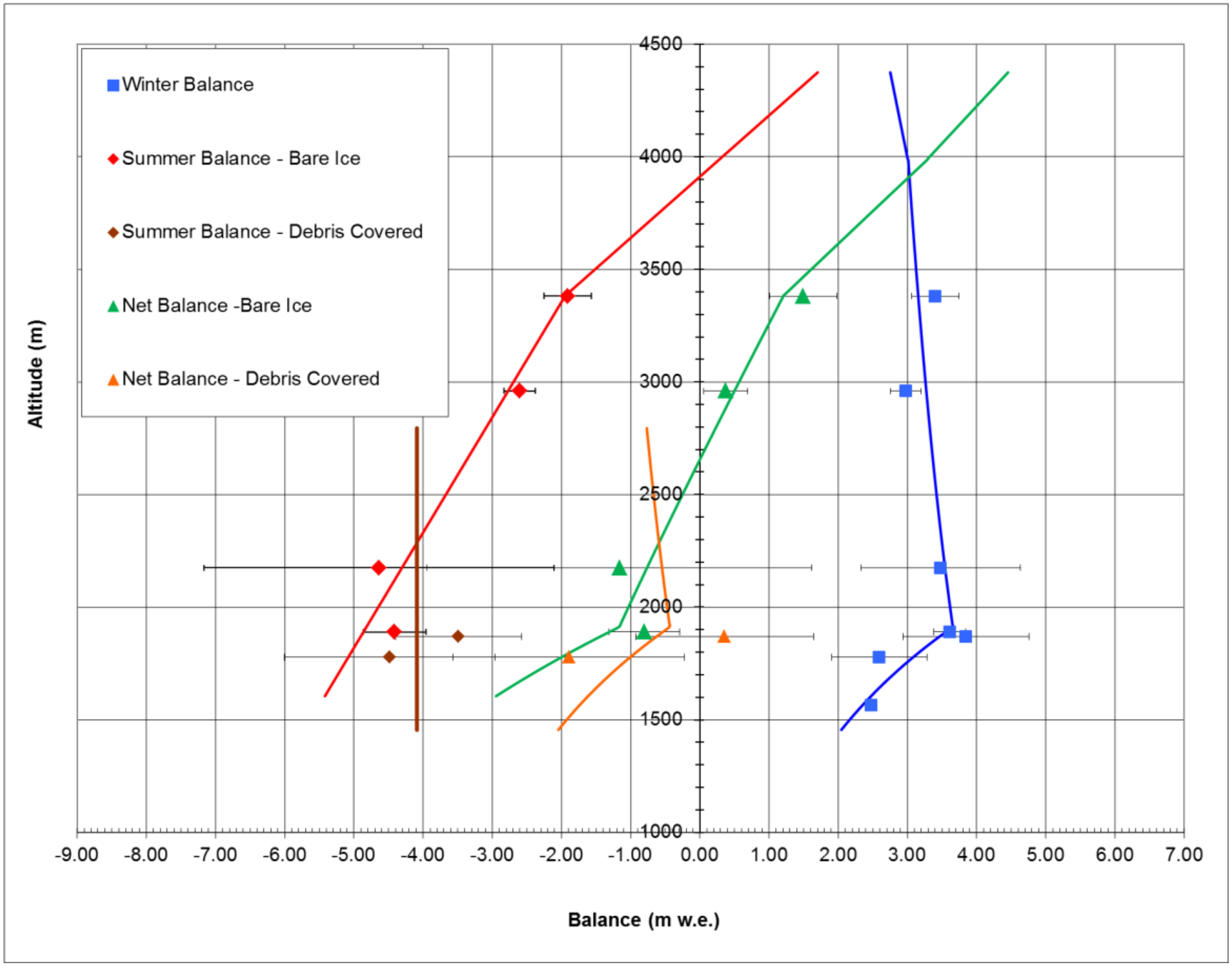

Figure 7. Estimated summer, winter, and net balance measured at varying altitudes on Nisqually Glacier in 2011.

Net Balance

This was the second consecutive year with a positive net balance for Nisqually Glacier [+0.44 (±1.26) m w.e.], which was likely aided by additional winter accumulation from snow avalanches originating from the upper mountain (Figure 8). The net mass balance for Emmons Glacier was slightly negative [-0.02 (±0.85) m w.e.; Figure 8]. Net balances for both glaciers were within the margin of error. Normally, the largest net loss occurs on the lowest elevation non-debris-covered portions of the glacier; on Emmons Glacier net balance was -4.56 m w.e at 1890 m (Figure 6). However, for Nisqually Glacier the largest net mass loss occurred near the debris-covered terminus, beyond the snow avalanche debris found at stakes 3, 4 and 4A (Figure 7). Based on extrapolated balance curves, there was a net gain of between 3.09 and 4.55 m w.e. on the summit of Mount Rainier.

The equilibrium line altitude (ELA) for Nisqually Glacier was lower and had a greater departure from average than the Emmons Glacier. The ELA for Nisqually Glacier was 2675 m, more than 500 m below the period of record average of 3180 m. The ELA for Emmons Glacier was 2640 m, approximately 150 m below the average of 2790 m. The volume change from these two glaciers in WY2011 is estimated at +2.96 million m^3 for Nisqually Glacier and -0.22 M m^3 for Emmons Glacier.

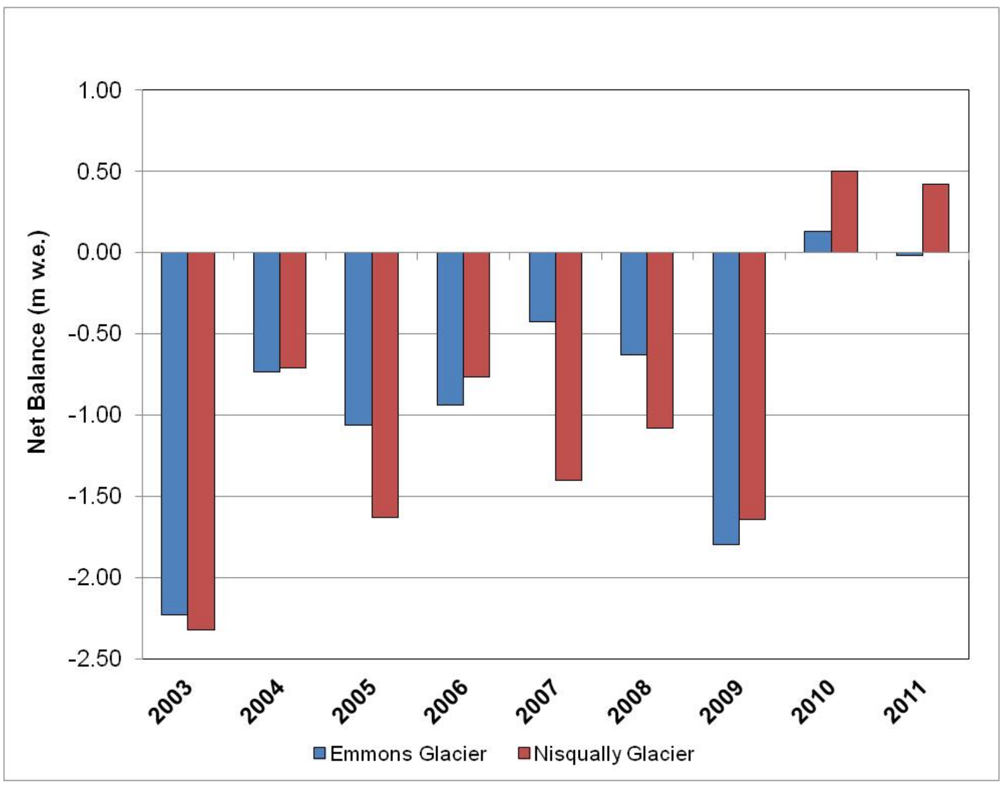

Figure 8. Net mass balance comparisons of Nisqually and Emmons Glaciers by water year.

Cumulative Balance

In WY2011, net mass balance for Nisqually Glacier was positive for the second consecutive year, however it was near neutral for the Emmons Glacier (Figure 9). The long-term trend in cumulative balance has been strongly negative for both glaciers. Since 2003, the cumulative balance for Nisqually Glacier is -8.61 m w.e. and for Emmons Glacier it is -7.71 m w.e. The cumulative net volume loss in the past nine years is 89.4 million m^3 and 58.2 million m^3 for Emmons and Nisqually glaciers, respectively.

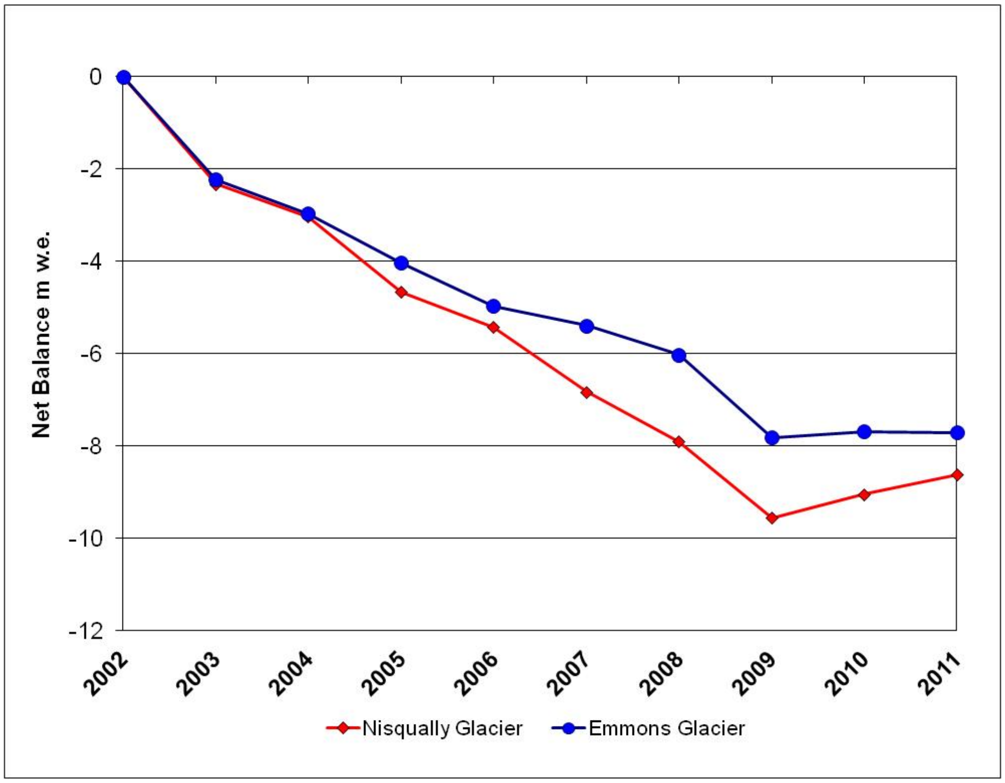

Figure 9. Cumulative balance for Nisqually and Emmons Glaciers by water year.

Glacial Contribution to Streamflow

The percent of glacial contribution to summer runoff was the lowest since monitoring began in 2003. In White River basin, glaciers contributed 65.2 M m^3 of water to streamflow between May 1 and September 30, representing about 9% of the total summer runoff (Table 2). Glaciers in the Nisqually basin contributed about 45.1 M m^3 to streamflow, or 12% of the total summer runoff. Streamflow is measured by USGS at the White River near Buckley and Nisqually River near National gaging stations (site numbers 12098500 and 12082500) (Figure 1).The volume of glacial contribution to summer runoff was the second and third lowest since monitoring began in 2003, representing 82 and 74% of the average contribution for the Nisqually River and White River watersheds, respectively.

Table 2. Glacier contribution to summer streamflow for two MORA watersheds. Average, minimum and maximum values are for water years 2003-2010.

Site (% glacier area)	May-September Runoff (million cubic meters)				Percent Glacial Runoff to Total Summer Runoff			
	2011	**average**	**min**	**max**	**2011**	**average**	**min**	**max**
Nisqually Glacier	19.2	23.7	17.3	30.2				
Nisqually River Watershed (4.6)	45.1	55.0	39.5	68.6	11.6	21.1	12.4	33.1
Emmons Glacier	27.5	37.5	27.4	58.4				
White River Watershed (2.4)	65.2	88.6	62.7	138.6	8.8	16.5	10.6	25.8

Since 2003, the range in total glacier melt-water contribution to Whiter River Basin is 62.7-138.6 M m^3 of water to summer streamflow, representing about 9-26% of the total. Glaciers in the Nisqually basin contribute between 39.5-68.6 M m^3 to summer streamflow, or about 12-33% of total runoff (Figure 10).

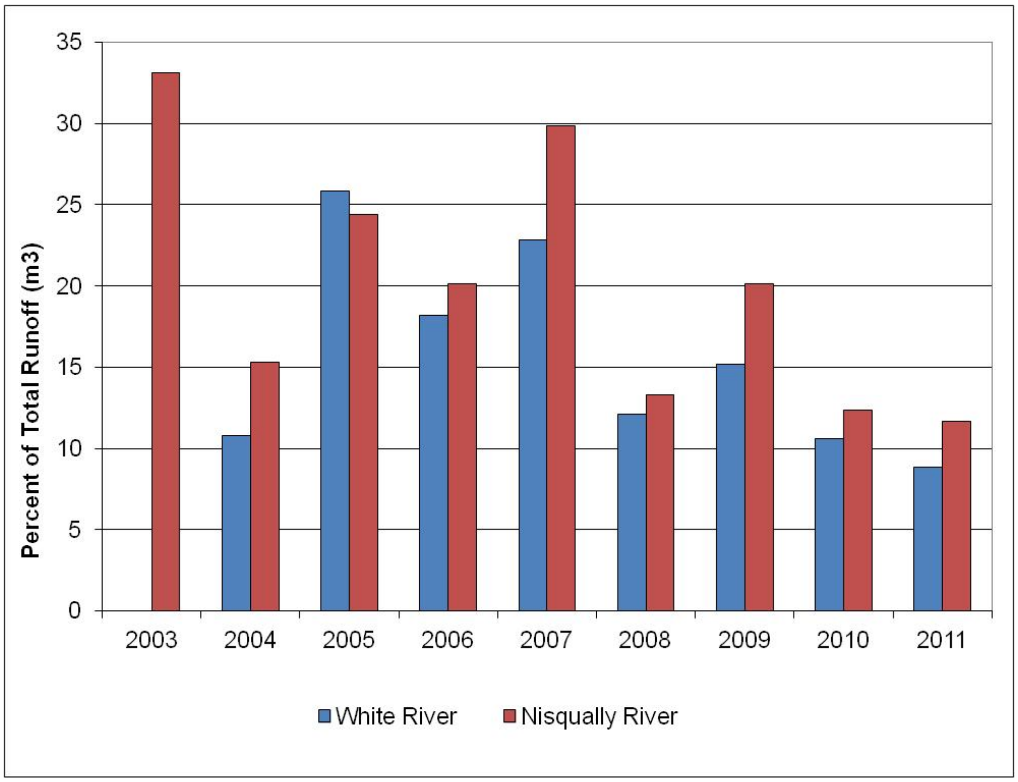

Figure 10. Total summer glacier meltwater contributions for two watersheds containing index glaciers.

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). A related noteworthy event, a large rock avalanche began depositing material onto the upper Nisqually Glacier (above stake 3) on June 24 (Figure 16 and 17). The rock avalanche originated from Nisqually Clever and continued to deposit material for several weeks.

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

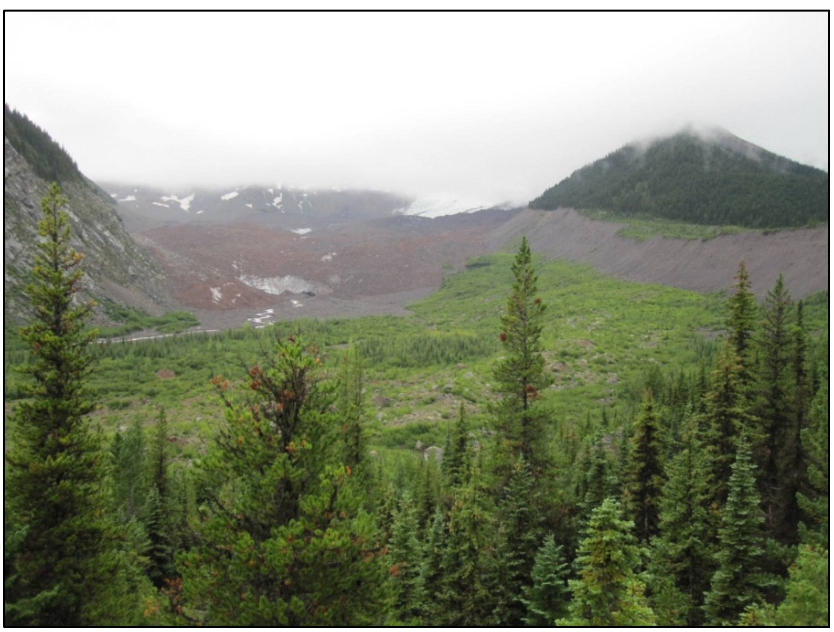

Figure 12. Emmons Glacier terminus, October 3, 2011. Photo taken from moraine photo-point. Cloud cover during the fall visit obscured the view of the glacier.

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

Figure 14. Nisqually Glacier, September 29, 2011. Photo taken from Glacier Vista.

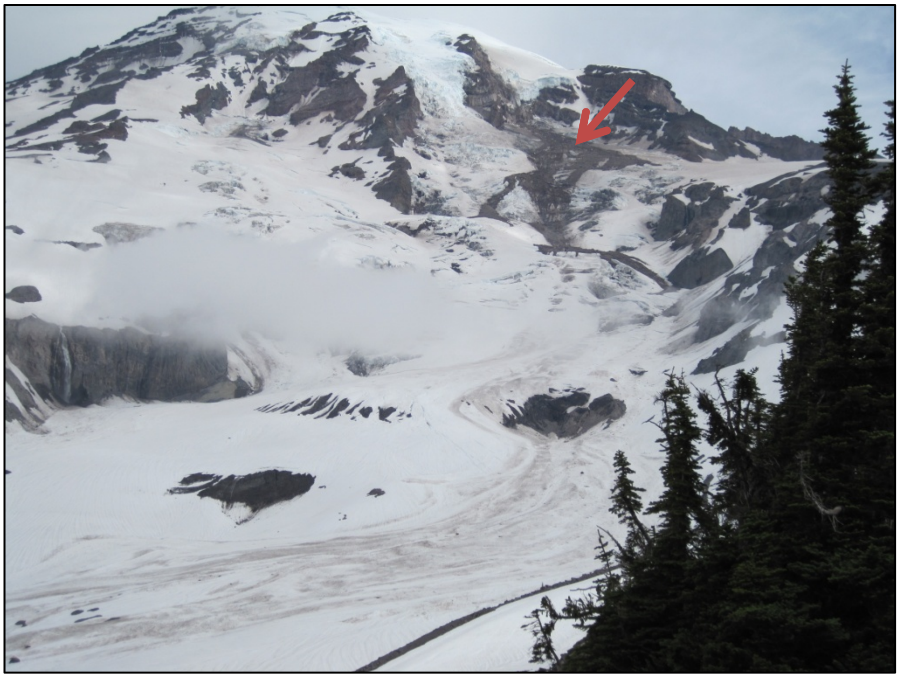

Figure 15. Rock avalanche deposits on the upper Nisqually Glacier (indicated with red arrow). Avalanching began on June 24, 2011, with accumulation continuing for several weeks. Photo taken on August 2, 2011 from Glacier Vista photo-point.

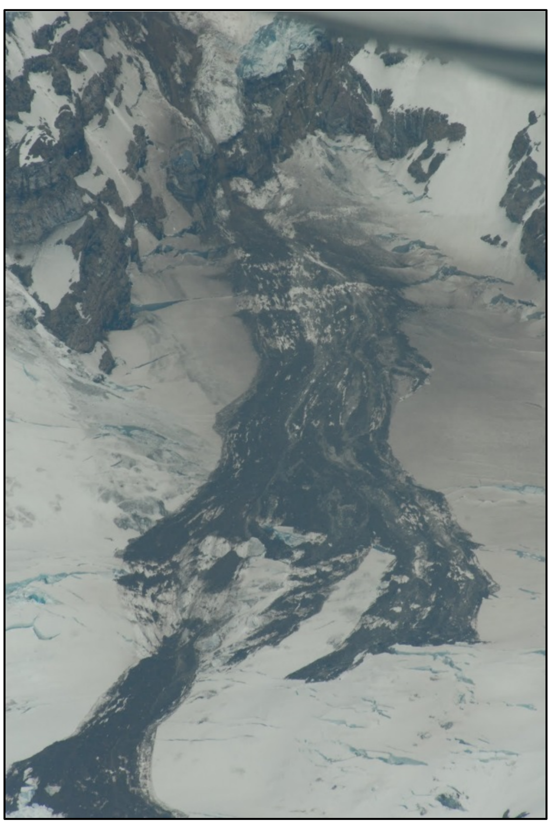

Figure 16. Aerial photo of rock avalanche on the upper Nisqually Glacier. Photo credit: Stefan Lofgren

Literature Cited

Driedger, C. L., and P. M Kennard. 1986. Ice volumes on Cascade volcanoes: Rainier, Mount Hood, Three Sisters, and Mount Shasta. Professional Paper 1365, U.S. Geological Survey.

Harrison, A. E. 1956. Fluctuations of the Nisqually Glacier, Mount Rainier, Washington, since 1750. *Journal of Glaciology* 2(19):675–683.

Hartzell, P. 2003. Glacial ecology: North Cascades glacier macroinvertebrates (2002 field season). Online report: http://www.nichols.edu/departments/Glacier/2002.htm, last updated January 2003.

Heliker, C. C., A. Johnson, and S. M., Hodge. 1983. The Nisqually Glacier, Mount Rainier, Washington, 1857–1979, A summary of long-term observations and a comprehensive bibliography. Open-File Report 84-541. U.S. Geological Survey.

Krimmel, R. M. 1994. Water, ice and meteorological measurements at South Cascade Glacier, Washington, 1993 Balance Year. Water-Resources Investigations Report 94-4139. U.S. Geological Survey, Tacoma, Washington.

Krimmel, R. M. 1995. Water, ice and meteorological measurements at South Cascade Glacier, Washington, 1994 Balance Year. Water-Resources Investigations Report 95-4139. U.S. Geological Survey, Tacoma, Washington.

Krimmel, R. M. 1996a. Water, ice and meteorological measurements at South Cascade Glacier, Washington, 1995 Balance Year. Water-Resources Investigations Report 96-4139. U.S. Geological Survey, Tacoma, Washington.

Krimmel, R. M. 1996b. Glacier mass balance using the grid-index method. Pages 62-68 *in* S. C. Colbeck, ed. Glaciers, ice sheets and volcanoes: A tribute to Mark F. Meier: U.S. Army Corps of Engineers Cold Region Research and Engineering Laboratory Special Report 96-27.

Krimmel, R. M. 1997. Water, ice and meteorological measurements at South Cascade Glacier, Washington, 1996 Balance Year. USGS WRI-97-4143. U.S. Geological Survey

Krimmel, R. M. 1998. Water, ice and meteorological measurements at South Cascade Glacier, Washington, 1997 Balance Year. USGS WRI-98-4090. U.S. Geological Survey

Krimmel, R. M. 1999a. Water, ice and meteorological measurements at South Cascade Glacier, Washington, 1998 Balance Year. USGS WRI-99-4049. U.S. Geological Survey

Krimmel, R. M. 1999b. Analysis of difference between direct and geodetic mass balance measurements at South Cascade Glacier, Washington. *Geografiska Annaler: Series A, Physical Geography* 81:653-658.

Krimmel, R. M. 2001. Water, ice, meteorological and speed measurements at South Cascade Glacier, Washington, 1999 Balance Year. USGS WRI-00-4265. U.S. Geological Survey

Meier, M. F. 1961. Mass budget of South Cascade Glacier, 1957-1960. U.S. Geological Survey Professional Paper 424-B. U.S. Geological Survey, Tacoma, Washington.

Meier, M. F., L. R. Mayo, and A. L. Post. 1971. Combined ice and water balances of Gulkana and Wolverine Glaciers, Alaska, and South Cascade Glacier, Washington, 1965 and 1966 hydrologic years. U.S. Geological Survey Professional Paper 715-A. U.S. Geological Survey, Tacoma, Washington.

Meier, M. F., and W. V. Tangborn. 1965. Net budget and flow of South Cascade Glacier, Washington. *Journal of Glaciology* 5(41):547-566.

Nylen, T. 2002. Spatial and temporal variation of glaciers on Mount Rainier between 1913-1994. Thesis. Portland State University, Portland, Oregon.

Østrem, G., and M. Brugman. 1991. Glacier mass balance measurements: A manual for field and office work. National Hydrology Research Institute, Inland Waters Directorate, Conservation and Protection Science Report No. 4. Environment Canada, Saskatoon, Saskatchewan, Canada.

Østrem, G., and A. Stanley. 1969. Glacier mass balance measurements - a manual for field and office measurements. The Canadian Department of Energy, Mines and Resources, and the Norwegian Water Resources and Electricity Board.

Paterson, W. S. B. 1981. The physics of glaciers. Pergamon Press, Elmsford, New York.

Riedel, J. L, R. A Burrows, and J. M. Wenger. 2008. Long term monitoring of small glaciers at North Cascades National Park: A prototype park model for the North Coast and Cascades Network. Natural Resource Report NPS/NCCN/NRR – 2008/066. U.S. National Park Service, Fort Collins, Colorado.

Riedel, J. L., J. M. Wenger, and N. D. Bowerman. 2010. Long term monitoring of glaciers at Mount Rainier National Park: Narrative and standard operating procedures version 1.0. Natural Resource Report NPS/NCCN/NRR – 2010/175. U.S. National Park Service, Fort Collins, Colorado.

Scott, K. M., J. W. Vallance, and P. T Pringle. 1995. Sedimentology, behavior, and hazards of debris flows at Mount Rainier, Washington. U.S. Geological Survey Professional Paper 1547. U.S. Geological Survey, Tacoma, Washington.

Tangborn, W. V., R. M. Krimmel, and M. F. Meier. 1971. A comparison of glacier mass balance by glaciological, hydrological, and mapping methods, South Cascade Glacier, Washington. Snow and Ice Symposium, IAHS-AISH Publication no. 104.

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