National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

North Cascades National Park Complex Glacier Mass Balance Monitoring Annual Report, Water Year 2010

North Coast and Cascades Network

Natural Resource Data Series NPS/NCCN/NRDS—2013/453

ON THE COVER
Summer 2010 field work on Noisy Glacier, North Cascades National Park
Photograph by: North Cascades National Park Complex

North Cascades National Park Complex Glacier Mass Balance Monitoring Annual Report, Water Year 2010

North Coast and Cascades Network

Natural Resource Data Series NPS/NCCN/NRDS—2013/453

Jon Riedel, Ph.D

North Coast and Cascades Network
National Park Service
North Cascades National Park Service Complex
810 State Route 20
Sedro-Woolley, WA 98284

Michael Larrabee

North Coast and Cascades Network
National Park Service
North Cascades National Park Service Complex
810 State Route 20
Sedro-Woolley, WA 98284

March 2013

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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/).

Please cite this publication as:

Riedel, J., and M. A. Larrabee. 2013. North Cascades National Park Complex glacier mass balance monitoring annual report, Water year 2010: North Coast and Cascades Network. Natural Resource Technical Report NPS/NCCN/NRDS—2013/453. National Park Service, Fort Collins, Colorado.

NPS 168/120074, March 2013

Contents

Page

Figures

Page

Tables

Page

Abstract

Glaciers cover approximately 109 km^2 in North Cascades National Park Service Complex (NOCA), and are a high-priority Vital Sign in the North Coast and Cascades Network monitoring plan because they are sensitive, dramatic indicators of climate change and drivers of aquatic and terrestrial ecosystems. Since 1993, seasonal volume changes at four NOCA glaciers have been monitored by tracking seasonal surface mass balance at four-to-five sites per glacier.

Water year 2010 was near average for winter accumulation for Noisy and Silver glaciers and slightly below average for Sandalee and North Klawatti glaciers. Winter mass balance ranged from 3.1 (±0.25) to 2.2 (±0.27) m water equivalent (w.e.). Summer melting was below average for all four glaciers and significantly below average for Silver, North Klawatti and Sandalee glaciers, ranging between 63 and 92 percent of average. Summer melt ranged between -1.5 (±0.42) m w.e. for Silver and -3.2 (±0.30) m w.e. for Noisy. Net mass balances in 2010 were slightly positive at two glaciers and negative at two glaciers. North Klawatti Glacier had the largest positive net mass balance at 0.39 (±0.09) m w.e, while Sandalee Glacier had the largest net loss of glacier mass balance at-0.17 (±0.42) m w.e..

Positive mass balances observed in water year 2010 resulted in only minor increases to the cumulative mass balance; doing little to offset the significant loss that was observed during the past half century. Since 1993, the cumulative balance for the four monitored glaciers is between -11.11 m w.e. and -8.25 m w.e.

Below average summer melt and near average snowpack led to below average glacial contribution to streamflow at NOCA. In four major watersheds glaciers contributed 286 M m^3 (75.6 B gallons) of water to park lakes and streams. In Thunder Creek, glaciers provided about 24% of total summer runoff, whereas in the more arid, less glaciated Ross Lake basin glaciers contributed less than 4%.

Ten-year remapping of Noisy and North Klawatti glaciers was completed in 2011 and led to significant adjustment to the base maps used for integration of point (stake) measurement to the entire glacier. Net vertical surface decline exceeded 60 m at the terminus of North Klawatti Glacier and 20 m on Noisy Glacier. Back-adjustment of data from 1993 - 2010 with the new hypsometry data resulted in minor changes to cumulative balance of -0.35 m w.e. on Noisy Glacier and +0.01 m w.e. on North Klawatti Glacier.

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 Benjamin Wright, Stephen Dorsch, and Sharon Brady. Erin Pettit, Michelle Koutnik and TJ Fudge of the University of Washington, Claire Todd of Pacific Lutheran University, and Rob Burrows, Jeannie Wenger and Niki Bowerman contributed valuable time, equipment, and expertise to the remapping of Noisy and North Klawatti glaciers. We want to thank Sarah Welch, Mark Huff, Hugh Anthony, and Jack Oelfke for their administrative support. We would also like to recognize peer-reviewers Rebecca Lofgren and Regina Rochefort, who substantially improved this report.

Introduction

The National Park Service began long-term monitoring of mass balance of glaciers within North Cascades National Park Complex (NOCA) in 1993. Monitoring includes direct field measurements of accumulation and melt to estimate volume gained and lost on a seasonal and water-year basis. Noisy Creek, Silver Creek, and North Klawatti Glaciers have been monitored at NOCA since 1993 and a fourth glacier, Sandalee, since 1995 (Figure 1). The purpose of this report is to describe field work and summarize data collected for water year 2010.

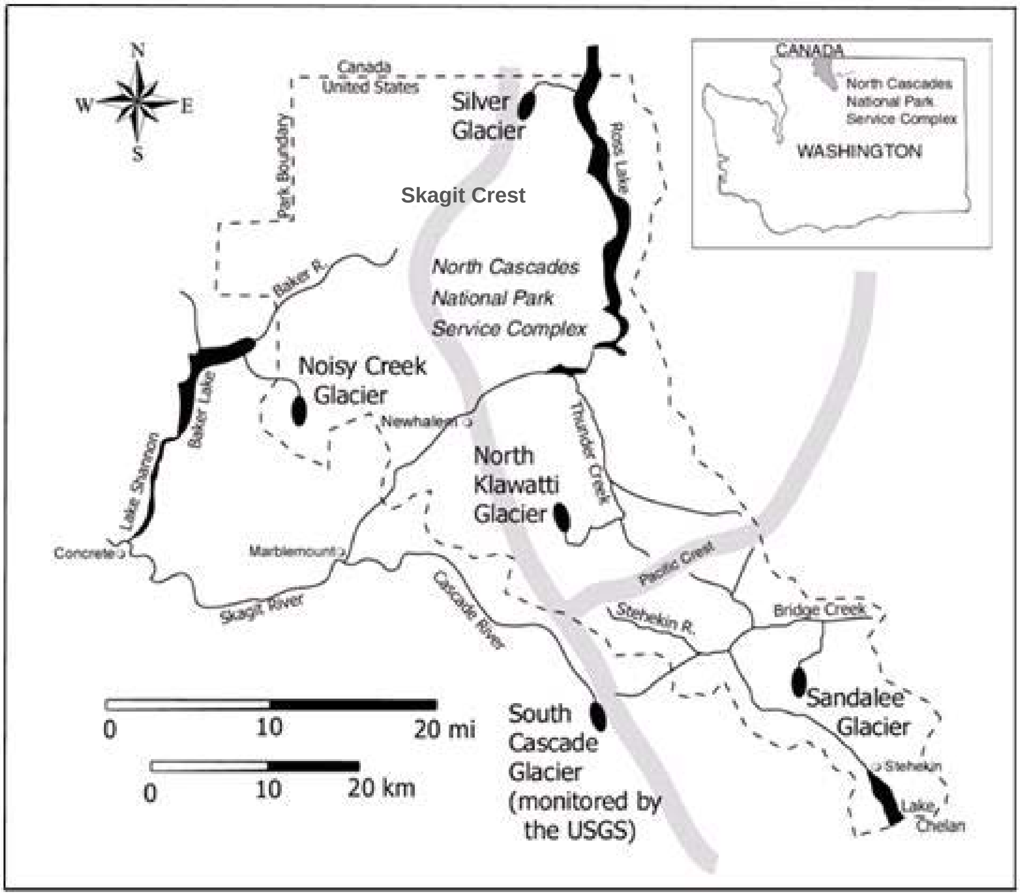

Figure 1. Locations of monitored glaciers and major hydrologic divides in the North Cascades (Riedel et al. 2008).

Glaciers are a significant resource of the Cascade Range in Washington State. North Cascades National Park contained 316 glaciers that covered 109 km^2 in a 1998 inventory (Granshaw 2001). They are integral components of the region's hydrologic, ecologic, and geologic systems. Glacial melt water delivery peaks during the hot, dry summers in the Pacific Northwest, buffering 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 within 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 important indicators of regional and global climate change. At North Cascades National Park, geologic mapping data, unpublished maps made by Austin Post, and a 1998 inventory (Granshaw and Fountain 2006) indicate that glacier area has declined ~50% in the last 100 years.

The four index glaciers monitored represent varying characteristics of glaciers found in the North Cascades, including altitude, aspect, and geographic location in relation to the main hydrologic crests (Figure 1). The glaciers selected drain into four major watersheds from NOCA and represent a 1000 meter range in altitude from the terminus of Noisy Glacier to the top of Silver Glacier.

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

1) Monitor range of variation and trends in volume of NOCA 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 the program goals include:

- 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 all index glaciers.
- Map and quantify surface elevation changes of all index 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 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.

Methods

Mass balance measurement methods used in this project generally follow procedures established during 45 years of research on the South Cascade Glacier by the USGS-Water Resources Division (Meier 1961, Meier and Tangborn 1965, Meier et al. 1971, Tangborn et al. 1971, Krimmel 1994, 1995, 1996, 1996a). They are very similar to those used around the world, as described by Ostrem and Stanley (1969), Paterson (1981), and Ostrem and Brugman (1991). Detailed procedures are outlined in Riedel et al. (2008).

Measurement System

We use a two-season stratigraphic approach to calculate mass gained (winter balance) and mass lost (summer balance) on a seasonal basis. Summation of these measurements allows for calculation of the net mass balance of a given glacier during the course of one water year (October 1-September 30). Measurements of accumulation and melt are made at around the same time every year in early spring and fall at approximately the same locations. Due to weather and logistical limitations, the actual maximum and minimum mass balance may not be recorded.

Winter balance is calculated from snow depth and bulk density measurements. Snow depth is measured at five to 10 points at four to five locations (ablation stakes) along the centerline of the glacier, resulting in 20-50 measurements per glacier. Snow density on each glacier is measured at the ablation stake location which is closest to the mid-point altitude of the glacier. When not directly measured, the average measured density of the spring snowpack since 1993 (0.5 +/- 0.05) is used. This value is also compared to values measured independently at SNOTEL[1] sites by the Natural Resource Conservation Service and at South Cascade Glacier by the U.S. Geological Survey.

Ablation stakes are used to measure summer balance. Stakes are placed in late April/early May when snow depth is probed for winter balance. Measurements of surface level change against the stakes are made in early to mid-summer and in late September to early October on each glacier. The change in ice, snow and firn elevation against the stake, while accounting for changes in the densities of firn and glacier ice, indicates the mass lost at the surface during the summer season (summer balance).

Oblique aerial photographs are taken of each index glacier as a record of change in area, surface elevation, equilibrium line altitude, and snow, firn and ice coverage. These color photographs are taken in early spring and late summer.

---

[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 SNOTEL stations located within North Cascade National Park (http://www.wcc.nrcs.usda.gov/snotel/Washington/washington.html).

Glacial Meltwater Discharge

Glacier contribution to summer streamflow is calculated annually in four park watersheds: Baker River, Thunder Creek, Ross Lake, and Stehekin River (Figure 1). The summer melt 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 ablation season. Selection of these dates means that runoff estimates from glaciers include snow as well as firn and ice.

A simple model is used to estimate glacier contributions to summer stream flow, and is based on the strong relationship between summer melt and altitude. This relationship is constrained by data from 18 melt stakes on four glaciers that spans 1000 m. Vertical melt at a given elevation from this curve is then multiplied by glacier area in 50 m bands derived by GIS, then summed for each watershed. The fraction of glacial melt-water to total summer runoff is determined at USGS gage sites on each river.

Glacier Mapping and Balance Adjustments

Accurate glacier maps are an important component of this monitoring program. Maps are used to assess area changes, advance/ retreat of termini, surface elevation/ volume changes, and to provide accurate base maps for mass balance calculations.

The area-altitude distribution of the four index glaciers are remapped every 10 years using vertical aerial photographs and high precision GPS point data. The original maps for Noisy and North Klawatti glaciers were made in 1994 based on photogrammetry from 1993 stereo air photos. The contractor used few control points and relied on USGS Quad coordinates and elevations. To improve the maps, benchmarks were installed and surveyed using a survey grade GPS in summer of 2005 and 2010 for Noisy Glacier and 2006 and 2008 for North Klawatti Glacier.

In addition to remapping of index glacier hypsometry every 10 years, the surface area of all park glaciers are remapped every 20 years. The park-wide inventory is based on vertical aerial photographs and was last completed in 1998 (Granshaw and Fountain 2006).

1993 to 2010 Record

In this report, we present data collected in 2010 and compare it to data collected from 1993-2009, using the methods described in Riedel et al. (2008). We present 18-year comparisons of winter, summer, net, and cumulative glacial balance, and summer glacial melt-water contributions to the Thunder Creek, Ross Lake and Baker and Stehekin River watersheds. A summary of the first decade of mass balance results was published in 2001 (Pelto and Riedel 2001).

Results

Measurement Error

Sources of error in mass balance estimates 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 2010 were largely above the period of record average (Table 1). Net balance error on Silver Glacier remained the highest of all four glaciers at ±0.50 m w.e. This was due to highly variable winter accumulation probe measurements caused by wind drifting of snow, avalanche deposits and a lack of summer surface layer development and low snow temperature.

Table 1. Calculated error for water year 2010 mass balance calculations for NOCA index glaciers, with period of record averages in parenthesis.

	Average Stake Error (m w.e.)		
Glacier	**Winter Balance**	**Summer Balance**	**Net Balance**
Noisy	±0.25 (0.20)	±0.30 (0.26)	±0.39 (0.31)
North Klawatti	±0.09 (0.20)	±0.09 (0.30)	±0.09 (0.31)
Sandalee	±0.24 (0.20)	±0.35 (0.27)	±0.42 (0.34)
Silver	±0.27 (0.26)	±0.42 (0.34)	±0.50 (0.43)

Winter and Summer Balance

Winter accumulation from October 2009 to April 2010 was near average at Noisy [3.12 (±0.25) m w.e.] and Silver [2.21 (±0.27) m w.e.] glaciers, and slightly below average at Sandalee [2.40 (±0.24) m w.e.] and North Klawatti [2.62 (±0.09) m w.e.] glaciers (Figure 2). Specific winter balance measured at individual stakes ranged from 4.10 (±0.36) m w.e. at Noisy Glacier to 1.83 (±0.35) m w.e. at Silver Glacier.

Summer melt in 2010 ranged between -1.52 (±0.42) at Silver Glacier and -3.22 (±0.30) m w.e. at Noisy Glacier. With the exception of Noisy Glacier, melt was significantly below average ranging between 63 and 80 percent of average; Noisy Glacier was 92 percent of average. Specific summer balance at individual stakes ranged from near -3.38 (±0.36) m w.e. at Noisy Glacier to less than -1.27 (±0.16) m w.e. on Silver Glacier.

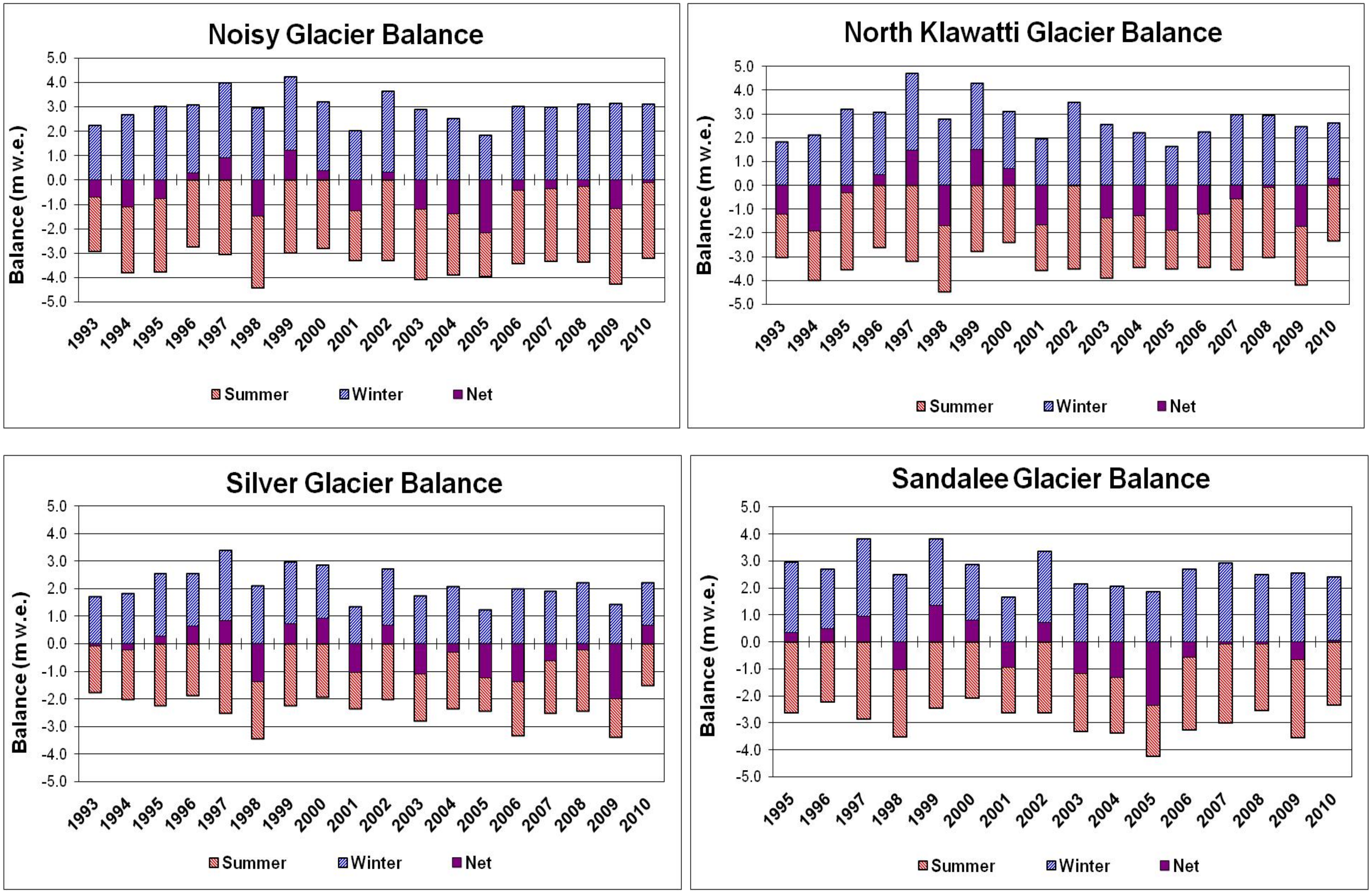

Figure 2. Winter, summer and net mass balances for each glacier by water year.

Net Balance

Annual net mass balances in water year 2010 were positive for North Klawatti and Silver glaciers, and negative for Sandalee and Noisy glaciers (Figures 2 and 3). The positive net balances recorded this year were the first after seven consecutive years with negative mass balances. North Klawatti Glacier had the most positive mass balance [0.39 (±0.09) m w.e.], while Sandalee Glacier had the most negative balance [-0.17 (±0.42) m w.e.].

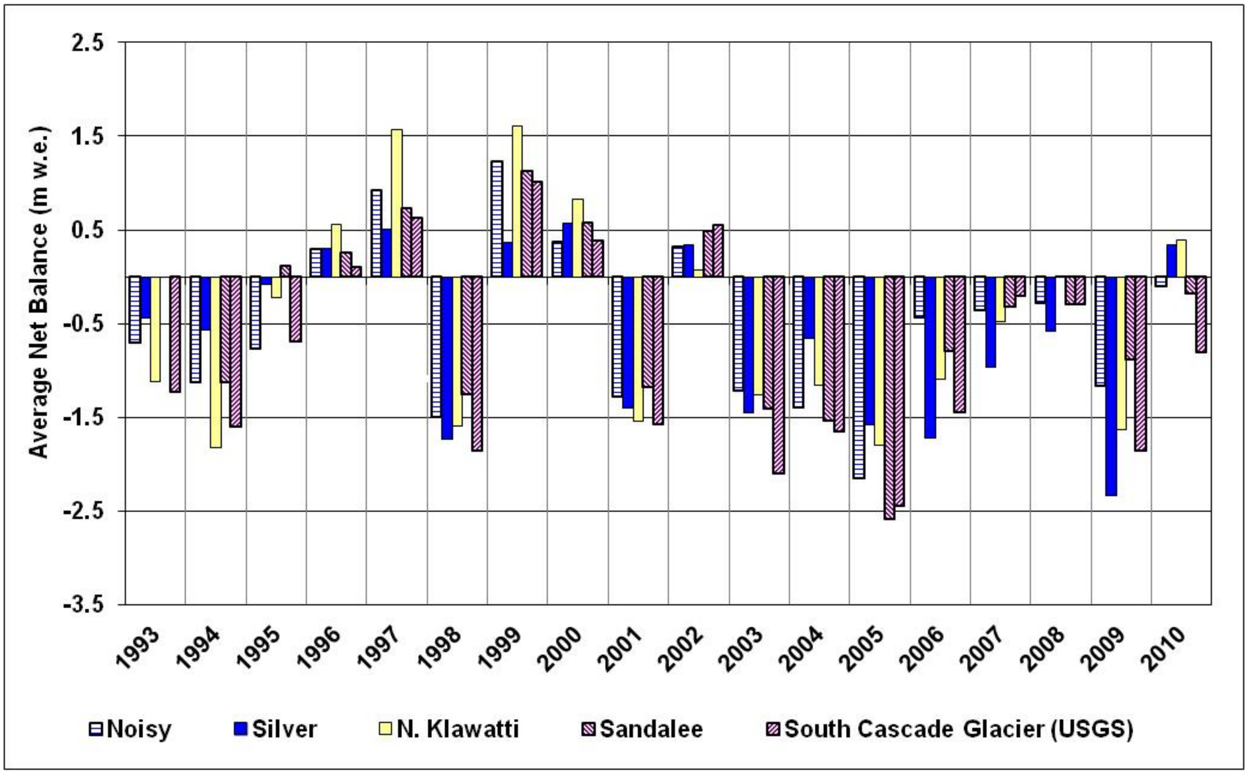

Figure 3. Adjusted net mass balance comparisons for each glacier by water year.

Cumulative Balance

Positive net balances measured at several of the index glaciers in 2010 resulted in a very minor increase in cumulative balance. However, the previous seven consecutive years of negative net mass balance for all four glaciers has driven cumulative balances deeply into negative territory (Figure 4). Since 1993, the cumulative balance for the four monitored glaciers has decreased between -11.11 m w.e. (Silver) and -8.25 m w.e. (Sandalee).

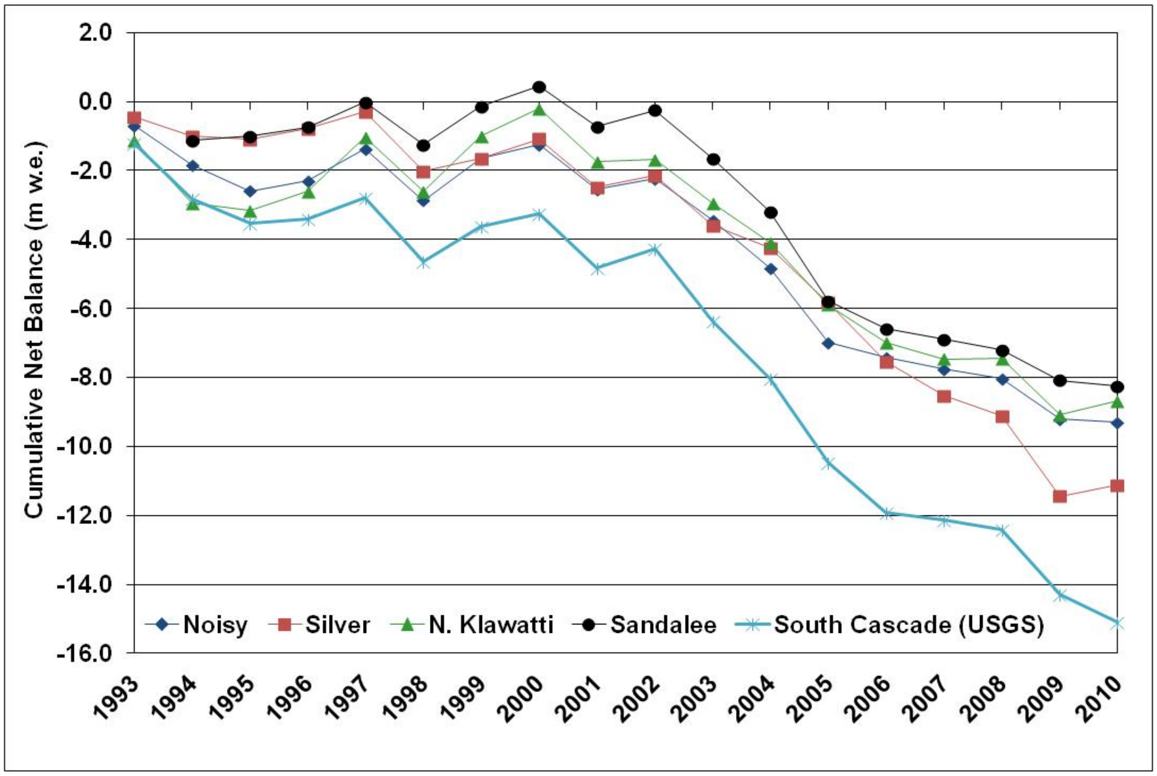

Figure 4. Adjusted cumulative balance for each glacier by water year includes South Cascade (USGS).

Glacial Contribution to Streamflow

Glacial contribution to runoff was below average in all watersheds due to below average summer melt. The total volume of melt water was the lowest since monitoring began and the percent of glacier contribution to summer streamflow was the 4th lowest (Table 2 and Figure 5). Depending on the basin, glacial contribution was 61-73 percent of average. Glaciers contributed a combined 286 M m^3 of meltwater to four watersheds. Contribution was the greatest in Thunder Creek watershed at 23.5 percent and lowest in the Ross Lake watershed at 3.4 percent.

Table 2. Glacial contribution to summer streamflow for four NOCA watersheds. Meltwater contributions are provided for each index glacier and from all glaciers within the watershed. In parenthesis is percent of total watershed area that is glaciated. Average, minimum and maximum values are calculated from 1993-2010 data.

Site (% area glaciated)	**May-September Runoff (million cubic meters)**				**Percent Glacial of Total Summer Runoff**			
	2010	**average**	**min**	**max**	**2010**	**average**	**min**	**max**
Baker River Watershed								
Noisy Creek Glacier	1.8	1.9	1.5	2.4				
All glaciers (6)	93.8	140.3	93.8	170.6	10.8	15.3	9.2	22.7
Thunder Creek Watershed								
North Klawatti Glacier	3.5	4.9	3.4	6.3				
All glaciers (13)	80.6	119.6	80.6	144.6	23.5	32.2	20.7	46.1
Stehekin River Watershed								
Sandalee Glacier	0.7	0.6	0.4	0.8				
All glaciers(3)	58.4	85.8	58.4	105.7	6.5	10.4	5.9	22.1
Ross Lake Watershed								
Silver Glacier	0.6	1.2	0.6	1.6				
All glaciers (1)	53.0	78.4	53.0	96.4	3.4	5.6	2.5	13.0

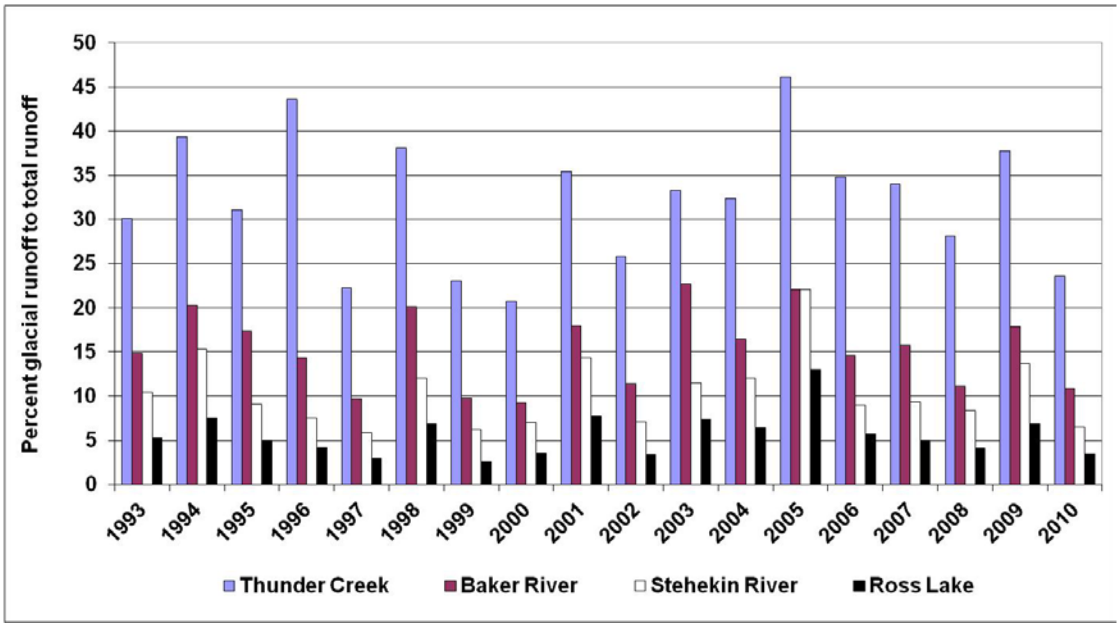

Figure 5. Total summer glacier meltwater contributions for the four watersheds containing a glacier monitored by North Cascades National Park.

Noisy and North Klawatti Glaciers Balance Adjustment

Tracking glacial change via contour maps and digital elevation models (DEMs) are important components of this monitoring program. In 2010, corrections were made to the original maps and new maps were created for Noisy and North Klawatti glaciers (Figures 6 and 7). The original base maps were adjusted using improved spatial data resulting from surveyed benchmarks that were installed adjacent to Noisy Glacier in 2005 and adjacent to North Klawatti 2006 and 2008. Remapping of North Klawatti and Noisy glaciers hypsometry was based on aerial photographs taken in 2006 and 2009 and high precision GPS point data collected in 2006 and 2010.

For more accurate and consistent mass balance results, the balance calculations were redone with this new information from both sets of new maps. From 1993-2000, Noisy and North Klawatti mass balance calculations were based on the corrected 1993/1996 maps. From 2001-2010, Noisy and North Klawatti mass balance calculations are based on the updated maps.

Comparison between corrected 1993 maps and the new 2006/2009 maps indicate the area of North Klawatti Glacier decreased 6% in this period, while the area of Noisy Glacier was reduced by 14%. Net vertical lowering (thickness) change exceeded 60 m at the terminus of North Klawatti Glacier and 20 m on Noisy Glacier.

Back-adjustment of data from 1993-2010 resulted in minor changes in cumulative balance and annual net balance. Cumulative balance decreased by -0.35 m w.e. on Noisy Glacier and increased by +0.01 m w.e. on North Klawatti Glacier.

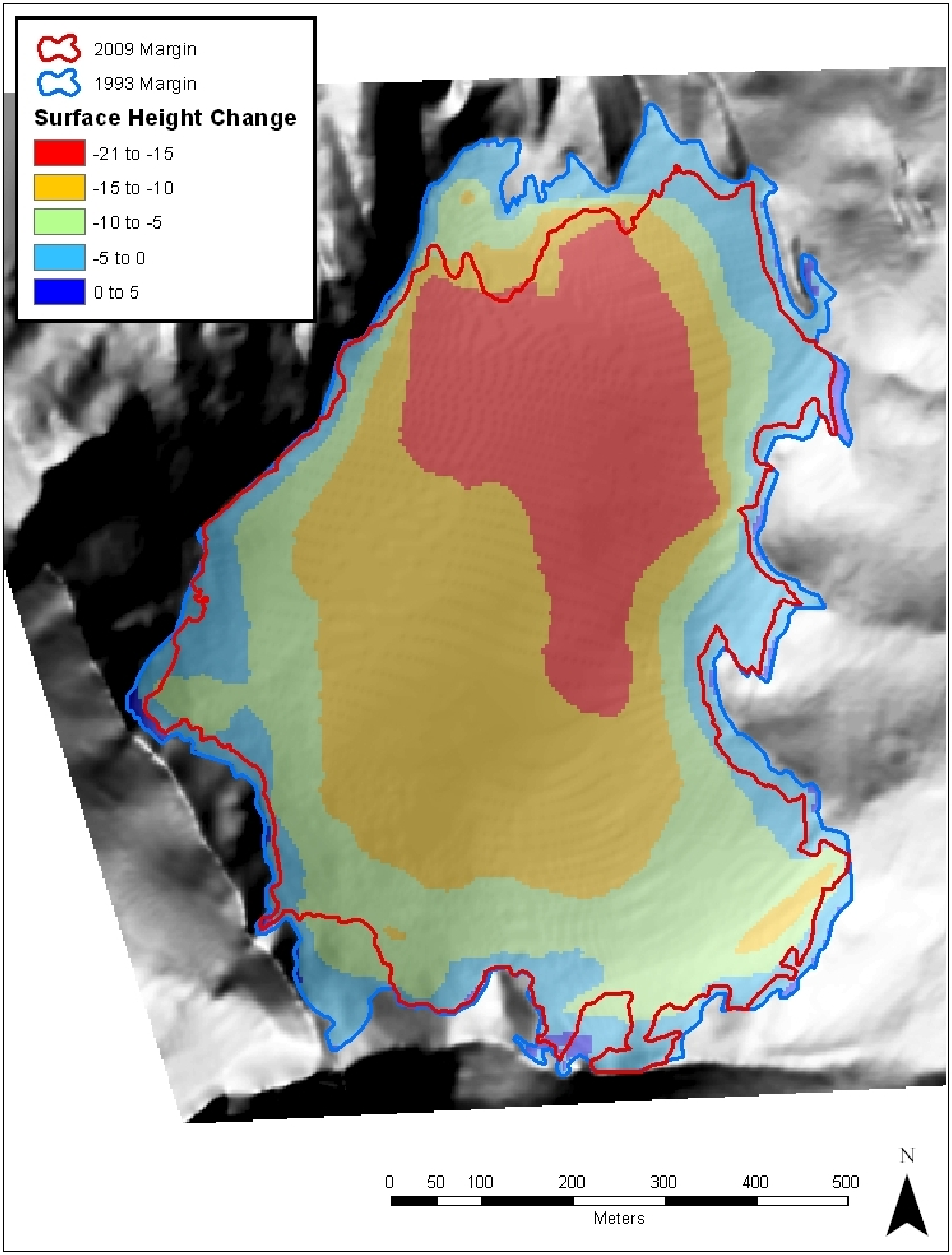

Figure 6. Noisy Glacier comparison of 1993 adjusted reference map and 2009/2010 balance map. Glacier surface elevation change is the difference between the 1993 surface (photogrammetry) and 2010 surfaces from photogrammetry and GPS.

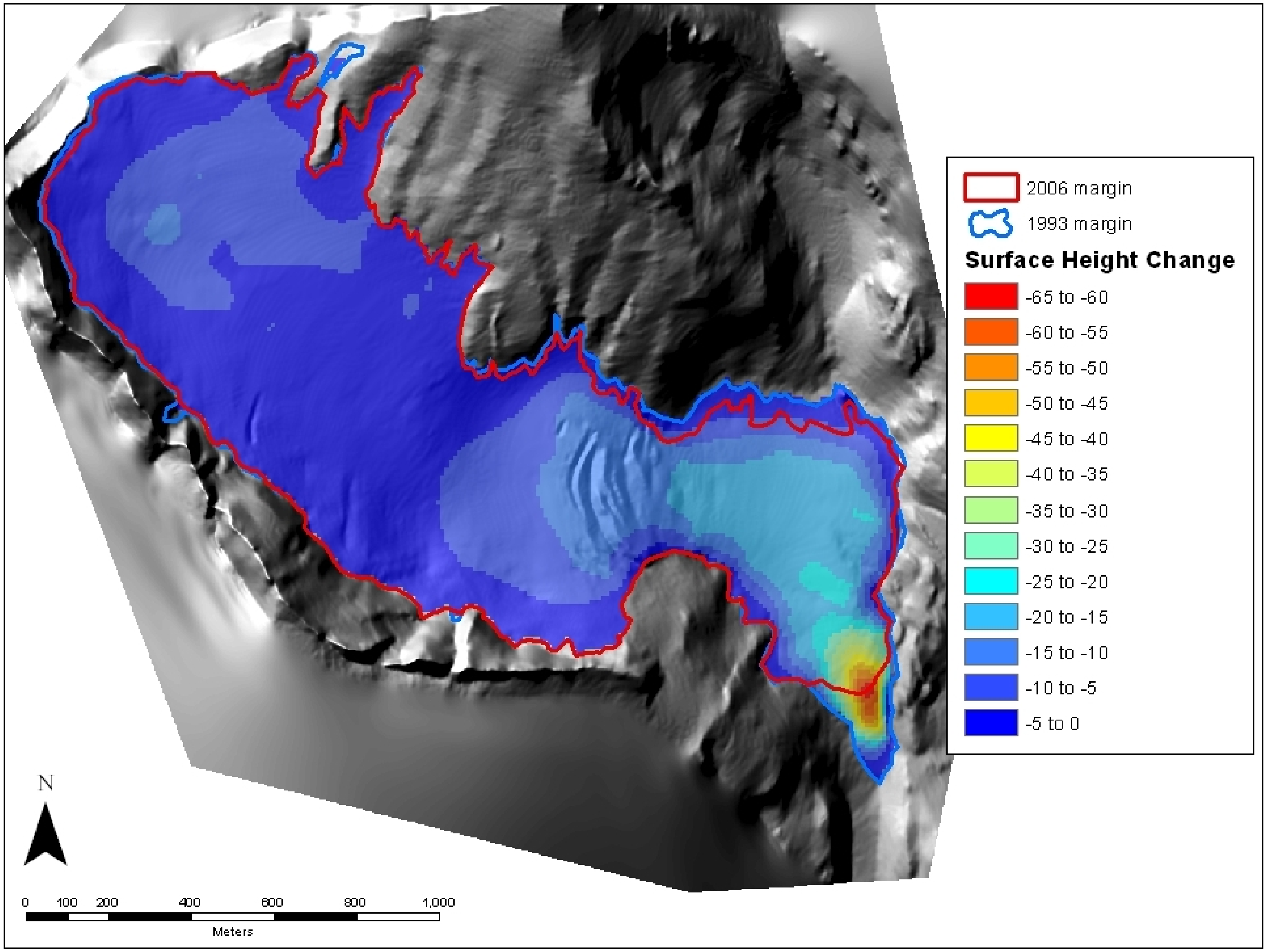

Figure 7. North Klawatti Glacier comparison of 1996 adjusted reference map and 2006/2009 balance map. Glacier surface elevation change is the difference between the 1996 surface (photogrammetry) and 2006 July surface from photogrammetry and GPS

Aerial Imagery

Oblique photographs of each index glacier are shown in Figures 8-12 as records of change in area, surface elevation, equilibrium line altitude, and snow, firn and ice coverage. Photos from previous years are provided for comparison. Glaciers in the fall 2010 pictures are covered with recently deposited snow, partially obscuring the snow, firn and ice boundaries. Cloud cover obscured visibility near Silver Glacier; therefore no fall 2010 photo was taken.

Figure 8. North Klawatti Glacier from east, September 24, 1993.

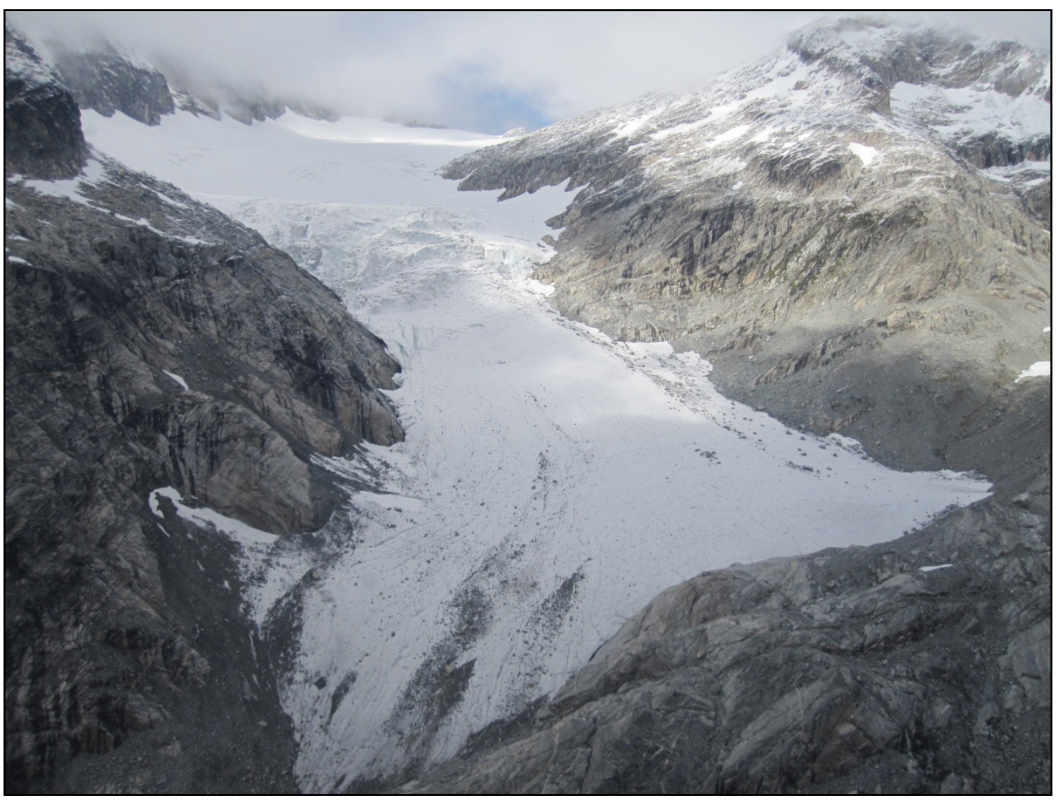

Figure 9. North Klawatti Glacier from east, September 21, 2010.

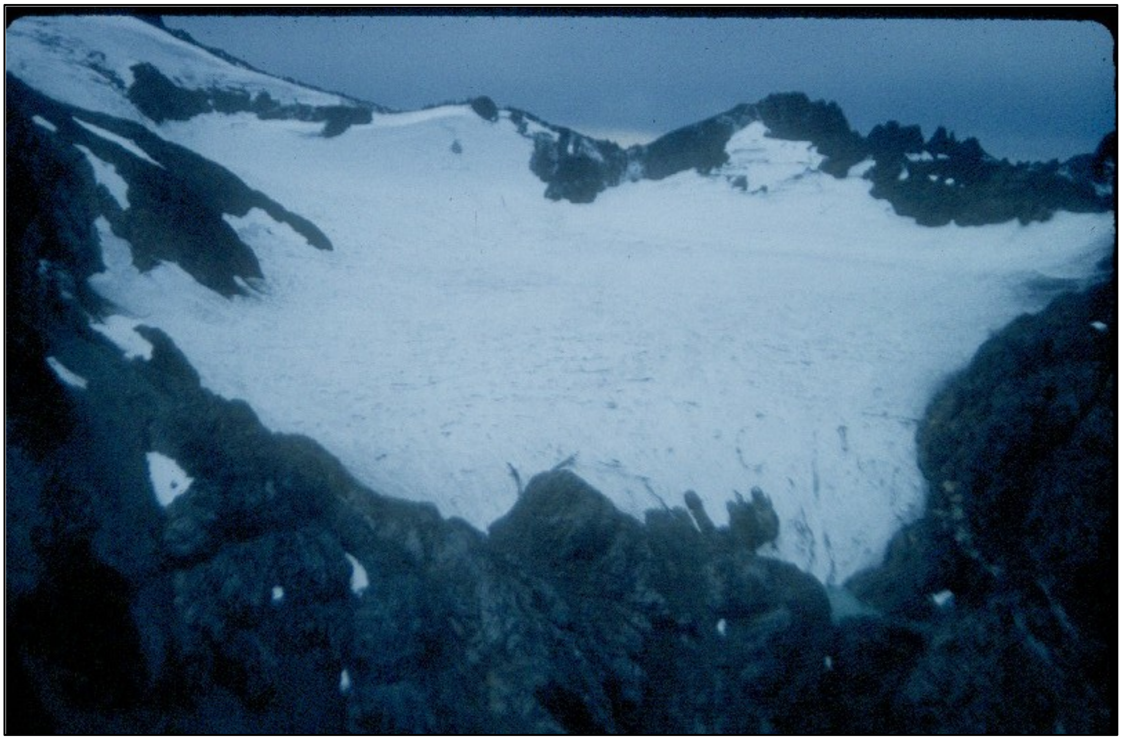

Figure 10. Noisy Glacier from north, September 24, 1993.

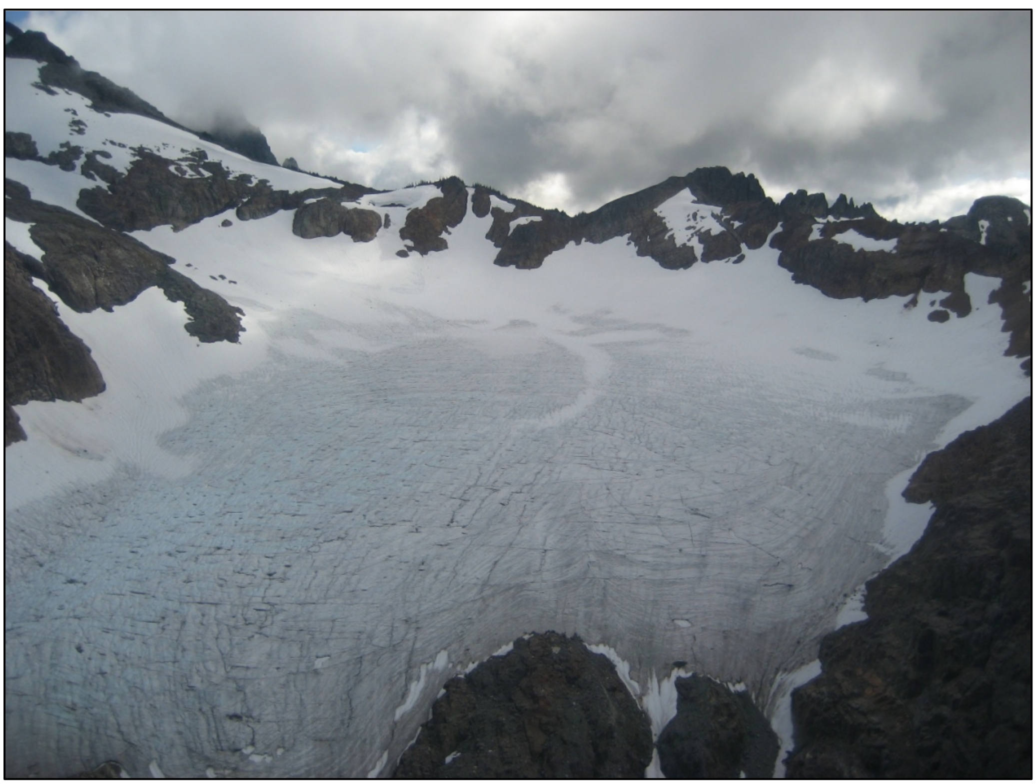

Figure 11. Noisy Glacier from north, September 21, 2010.

Figure 12. Sandalee Glacier from east, October 3, 1994 (left) and from north, September 21, 2010 (right).

Literature Cited

Granshaw, F. D. 2001. Glacier change in the North Cascades National Park Complex, Washington State USA, 1985-1998. Master's Thesis, Portland State University, Portland, Oregon.

Granshaw, F. D., and A. G. Fountain. 2006. Glacier change (1958-1998) in the North Cascades National Park Complex, Washington, USA. Journal of Glaciology 52(177):251-256.

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.

Hodge, S. M., D. C. Trabant, R. M. Krimmel, T. A. Heinrichs, R. S. March, and E. G. Josberger. 1998. Climate variations and changes in mass of three glaciers in western North America. Journal of Climate 11(9):2161-2179.

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. 1996. 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. 1996a. 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.

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.

Ostrem, 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.

Ostrem, 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, New York.

Pelto, M. S., and J. L. Riedel. 2001. Spatial and temporal variations in annual balance of North Cascade Glaciers, Washington 1984-2000. Hydrologic Processes 15:3461-3472.

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.

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.