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Natural Resource Stewardship and Science

North Cascades National Park Complex Glacier Mass Balance Monitoring Annual Report, Water Year 2011

North Coast and Cascades Network

Natural Resource Data Series NPS/NCCN/NRDS—2013/483

ON THE COVER
Spring 2011 field work on Sandalee Glacier, North Cascades National Park
Photograph by: North Cascades National Park Complex

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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 website (http://science.nature.nps.gov/im/units/nccn/reportpubs.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

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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 (NCCN) monitoring plan because they are sensitive, dramatic indicators of climate change and drivers of aquatic and terrestrial ecosystems (Reidel et al. 2008). Since 1993, seasonal volume changes at four NOCA glaciers have been monitored using methods developed as part of the NCCN Glacier Monitoring Protocol (Reidel et al, 2008).

During water year (WY) 2011, winter accumulation was above average for all glaciers. Winter mass balance ranged from 2.40 (±0.31) to 4.05 (±0.30) m water equivalent (w.e.). Summer melting was below average for all four glaciers, ranging from 70-84 percent of average. Summer balance ranged from -1.68 (±0.23) m w.e. to -2.82 (±0.32) m w.e. At Silver Glacier, recorded summer melt was the second lowest since monitoring began in 1993. Net mass balances in WY 2011 were positive for all four glaciers, the second consecutive year with positive balances recorded. At Noisy Glacier, net balance was the second largest since 1993. Net mass balances ranged from 0.37 (±0.42) to 1.24 (±0.32) m w.e. Equilibrium line altitudes ranged from 1620 to 2030 m; between 157 to 338 m below the 1993-2011 average.

Positive mass balances observed in WY 2011 resulted in minor increases to the cumulative mass balance; doing little to offset significant losses observed during the past half century. Since 1993, the cumulative balance for the four monitored glaciers is between -10.84 m w.e. and -7.34 m w.e.

Below average summer melt led to below average relative glacial contribution to streamflow at NOCA. Four major watershed glaciers contributed 311M m^3 of water to park lakes and streams. In Thunder Creek, glaciers provided about 22% of total summer runoff, whereas in the more arid, less glaciated Ross Lake basin, glaciers contributed less than 3% due to the heavy winter snowpack and low summer melt rates.

Acknowledgments

Measurement of mass balance on four glaciers 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. 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 Bill Baccus and Natasha Antonova, who substantially improved this report.

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 glacier mass balance within North Cascades National Park Complex (NOCA) in 1993. Monitoring includes direct field measurements of accumulation and melt to estimate the 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). This report describes field work and summarizes data collected for water year (WY) 2011.

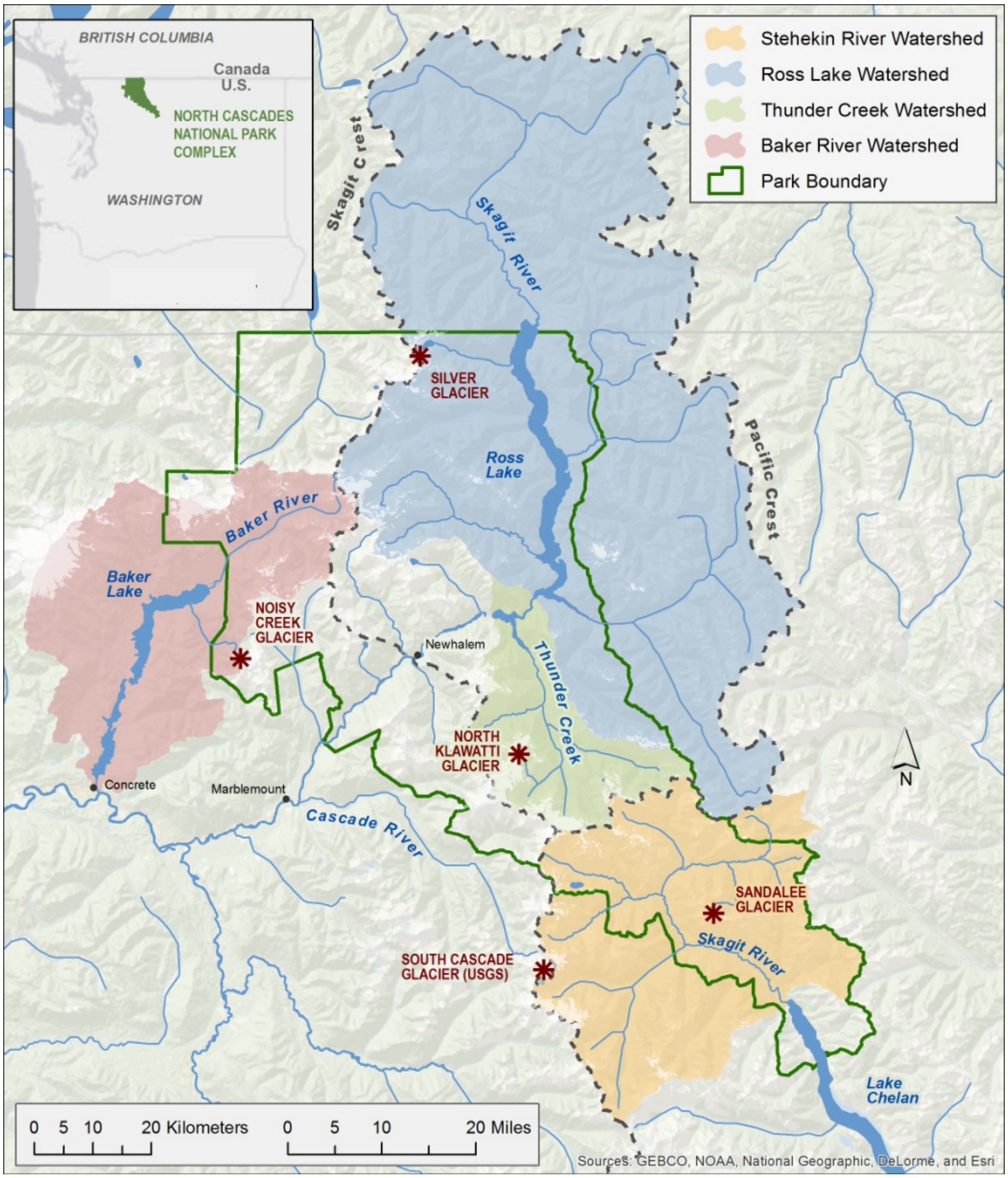

Figure 1. Locations of monitored glaciers and major hydrologic divides in the North Cascades National Park Complex (Riedel et al. 2008).

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). Glaciers are integral components of the region's hydrologic, ecologic and geologic systems. Delivery of glacial melt water 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 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 through 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 that were created by glaciers within the last century. Further, glaciers provide habitat for a number of species, and are the sole habitat for ice worms (*Mesenchytraeus solifugus*) and certain species of springtail arthropods (*Collembola;* Hartzell 2003).

Glaciers are also important indicators of regional and global climate change. At North Cascades National Park, glacial extent determined from neoglacial moraines, unpublished maps made by from USGS geologist Austin Post in the 1950's, and a 1998 inventory (Granshaw and Fountain 2006) indicate that glacier area has declined ~50% in the last 100 years.

The four NOCA index glaciers monitored by the NCCN represent varying characteristics of glaciers found in the North Cascades range, including altitude, aspect, and geographic location in relation to the main hydrologic crests (Figure 1). The glaciers selected drain into four major park watersheds and represent a 1000 meter range in altitude from the terminus of Noisy Glacier (1685 m) to the top of Silver Glacier (2705 m).

Glacier monitoring at NOCA has four broad goals:

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

- Collect a network of surface mass balance measurements sufficient 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.

1993 to 2011 Record

In this report, we present NOCA glacial mass balance data measured in water year 2011 and compare it to data collected from water years 1993-2010. We present 19-year comparisons of winter, summer, net, and cumulative glacial balance, and summer glacial meltwater contributions to the Thunder Creek, Ross Lake, Baker, and Stehekin River watersheds. A more detailed summary of the first decade of mass balance results was published by Pelto and Riedel (2001).

Methods

Mass balance measurement methods used in this project are based on 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 glacial mass gained (winter balance) and glacial 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 ablation are made at around the same time every year in early spring and fall at approximately the same locations. Sampling dates coincide roughly with the actual maximum and minimum mass balances, but may vary due to weather and logistical limitations. Field measurements of winter balance occurred on April 19 and May 19, 2011.

Winter balance is calculated from snow depth and bulk density measurements. Snow depth is measured at ten points at 4-5 fixed stations along the centerline of each glacier resulting in 40-50 measurements per glacier. Snow density on each glacier is measured at the station that 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 during field visits in early spring and late summer.

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[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 Complex (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 the ablation season. Selection of these dates means that runoff estimates from glaciers include snow as well as firn and ice.

A simple model, based on the strong relationship between summer ablation and altitude, is used to estimate glacier contributions to summer stream flow. Ablation and elevation data are collected from 18 ablation stakes on four glaciers. Data taken at these stakes are used to generate a melt balance curve inferring vertical ablation values along elevation gradient. For 1993 and 1994, prior to monitoring at Sandalee Glacier, the melt balance curve is calculated from the remaining three glaciers. For each glacier, surface area for each 50 meter elevation band is calculated using GIS. The band area is multiplied by the corresponding vertical ablation value, which is derived from the melt balance curve by using the mean elevation of the corresponding band. The resulting values are summed for each watershed. The proportion of glacial meltwater is then determined by comparing it to total summer runoff measured at USGS gage sites on each river.

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 four 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 glacial 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. 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 WY 2011 were mostly above the period of record average (the exception being Silver Glacier; Table 1). Net balance error on Sandalee Glacier was the highest of all four glaciers at ±0.46 m water equivalent (w.e.). This was due to highly variable snow depth caused by avalanche deposits on the glacier surface.

Table 1. Calculated error for water year 2011 mass balance calculations for North Cascades National Park Complex index glaciers, with period of record averages in parentheses.

	Average Stake Error (m w.e.)		
Glacier	**Winter Balance**	**Summer Balance**	**Net Balance**
Noisy Creek	±0.30 (0.20)	±0.30 (0.26)	±0.42 (0.32)
North Klawatti	±0.31 (0.20)	±0.42 (0.31)	±0.37 (0.31)
Sandalee	±0.32 (0.20)	±0.32 (0.27)	±0.46 (0.34)
Silver	±0.23 (0.26)	±0.23 (0.33)	±0.32 (0.42)

Winter and Summer Balance

Spring weather conditions delayed site visits, resulting in a month lapse between measurements. Between visits, the snowpack began consolidating and snow depth lowered by 0.20 m at Noisy Glacier (1772 m).

Winter accumulation from October 2010 to April/ May 2011 was 111 to134 percent of average for the four NOCA index glaciers (Table 2, Figure 2). Winter accumulation in WY 2011 was the highest at Noisy Glacier [4.05 (±0.30) m w.e.], which was also the highest winter accumulation for this glacier since 1993. Winter balance was the lowest at Silver Glacier [2.40 (±0.23) m w.e.]. The largest winter balance for an individual stake (point winter balance) was measured at the lowest stake on Sandalee Glacier (4.90 (±0.51) m w.e.) due to a large accumulation of avalanche debris. The largest point winter balance not influenced by snow from avalanches was measured at Noisy Glacier at 4.78 (±0.29) m w.e. The smallest point winter balance was measured on Silver Glacier at 2.09 (±0.33) m w.e.

Summer melt in 2011 was 70-84 percent of average for the four index glaciers (Table 2, Figure 2). It was the second lowest melt measured since 1993 at Silver Glacier [-1.68 (±0.23) m w.e.], which has the highest mean elevation among the four NOCA glaciers. Summer melt was greatest at Noisy Glacier [-2.82 (±0.30) m w.e.], which has the lowest mean elevation. Point summer balance ranged from a low of -1.39 (± 0.18) m w.e. at 2538 m on Silver Glacier, the location of the highest monitoring stake; to a high of -4.12 (± 0.58) m w.e. at 1826 m on North Klawatti Glacier, the lowest stake on the glacier's southeasterly facing terminus.

Table 2. WY2011 mass balances and equilibrium line altitudes (ELA) for four index glaciers monitored at North Cascades National Park Complex. The period of record for Noisy Creek, North Klawatti and Silver glaciers is 1993-2011, and for Sandalee Glacier it is 1995-2011.

	Winter Balance (m w.e.)		**Summer Balance (m w.e.)**		**Net Balance (m w.e.)**		**ELA (m)**	
	2011	**Average**	**2011**	**Average**	**2011**	**Average**	**2011**	**Average**
Noisy Cr.	4.09	3.03	-2.82	-3.46	1.28	-0.43	1595	1842
N. Klawatti	3.58	2.83	-2.82	-3.35	0.75	-0.52	1998	2171
Silver	2.40	2.17	-1.68	-2.38	0.73	-0.22	2030	2368
Sandalee	3.23	2.71	-2.09	-2.87	1.15	-0.14	2010	2167

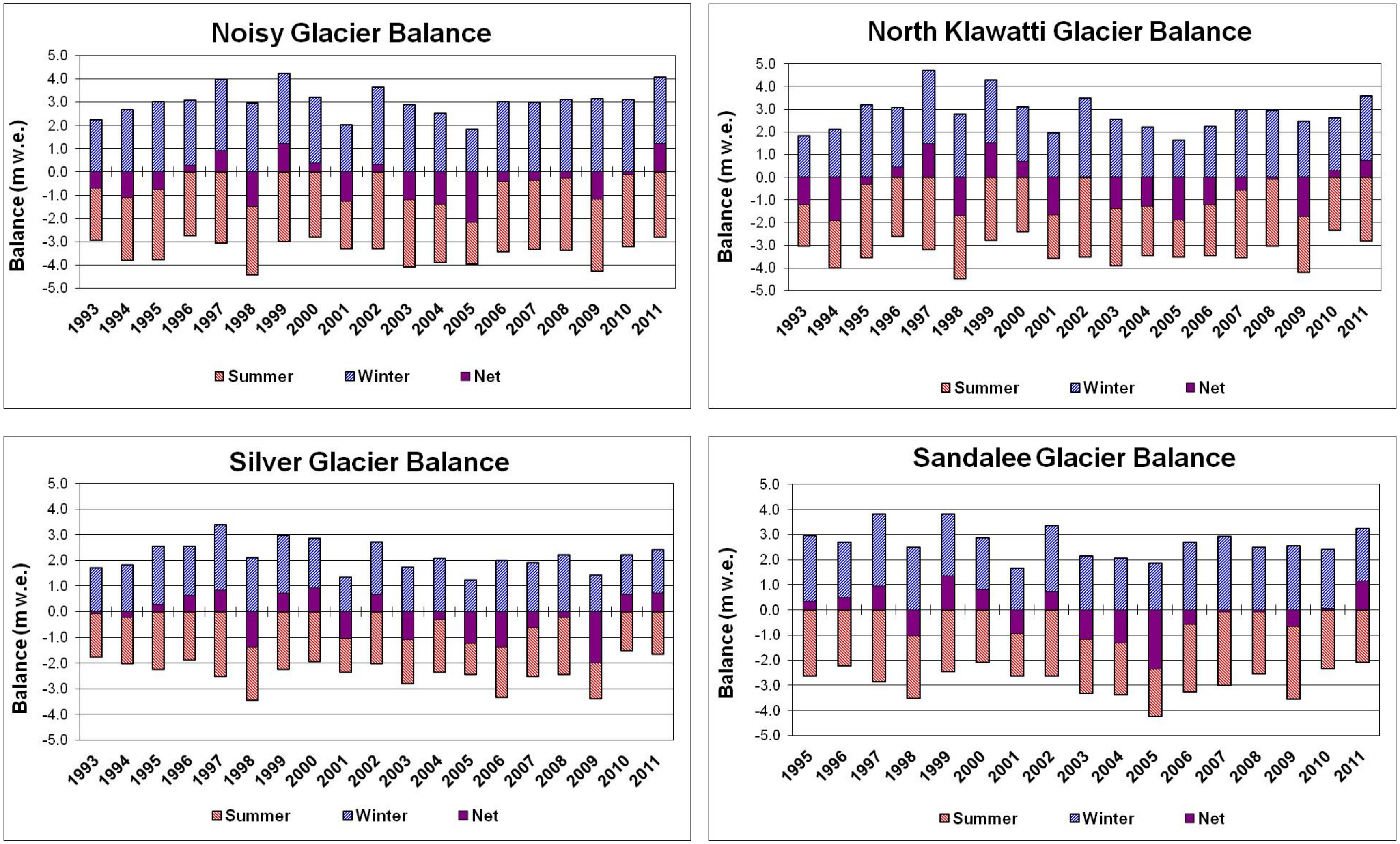

Figure 2. Winter, summer and net mass balances of four North Cascades National Park Complex index glaciers for water years 1993 to 2011.

Net Balance

Annual net mass balances in WY 2011 were positive for all four glaciers (Table 2, Figures 2 and 3). This was the second consecutive year with positive net balances recorded for Silver and North Klawatti glaciers and the first time in nine years when all four glaciers had positive net balances. Adjusted net balances ranged from 0.37 (±0.42) m w.e. at Silver Glacier to 1.24 (±0.32) m w.e at Noisy Glacier. WY 2011was the largest volume gain at Noisy and Sandalee glaciers since 1993. The range in volume gain in WY 2011 is estimated between 8.95K m^3 for the large North Klawatti Glacier and 1.28K m^3 for the much smaller Sandalee Glacier.

The largest net balance for an individual stake (point net balance) was measured at the lowest stake on Sandalee Glacier, a value of 2.26 (±0.72) m w.e. This was due to a large winter balance aided by avalanche deposits and topographic shading at the stake. The range of point net balance not influenced by avalanche deposits was 1.57 (±0.41) to -1.59 (±0.62) m w.e. (Noisy at 1830 m; North Klawatti at 1826 m).

Depending on the glacier, the balanced-budget equilibrium line altitude (ELA) ranged between 1620 and 2030 m (Noisy and Silver glaciers, respectively; Table 2). The WY 2011 ELA was between 157 to 338 m below the period of record average.

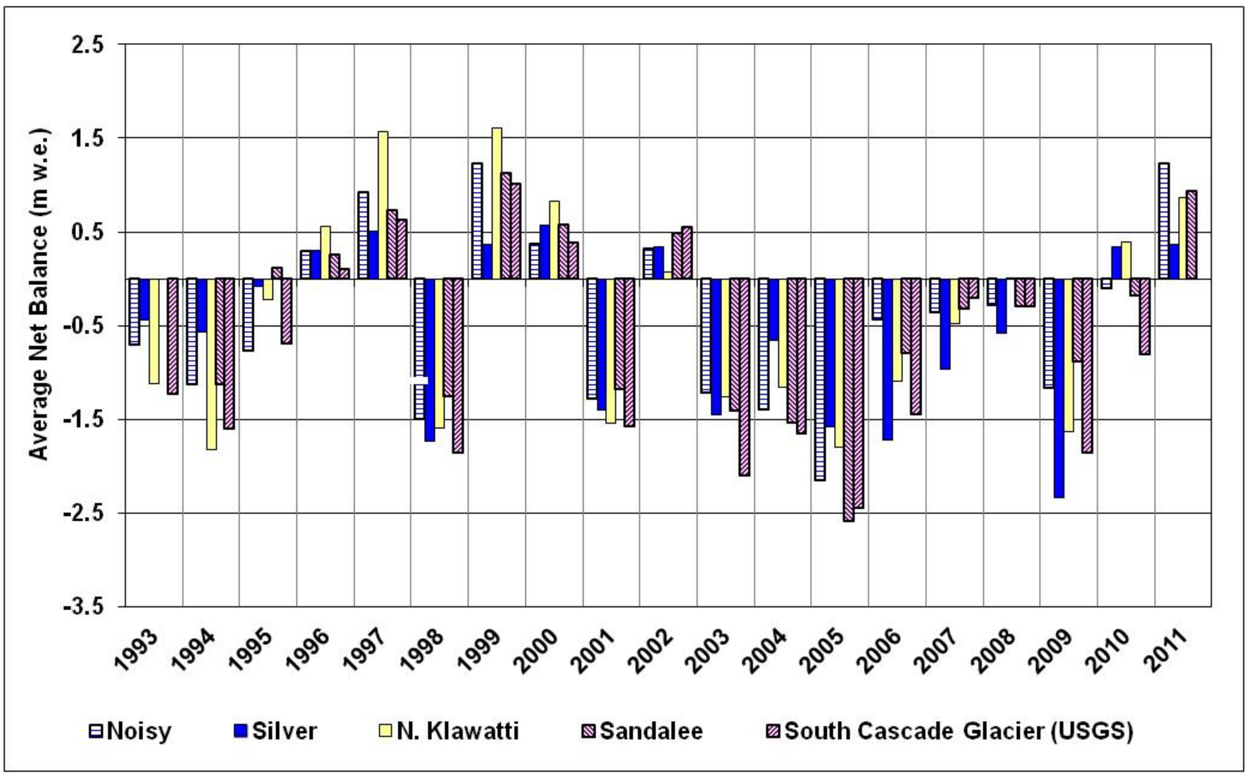

Figure 3. Adjusted net mass balance comparisons for each glacier by water year.

Cumulative Balance

Positive net balances measured at all four NOCA index glaciers in WY 2011 resulted in minor increases in cumulative balance. However, large negative net mass balances for all four glaciers observed since 2003 has driven cumulative balances deeply into negative territory (Figure 4). From 1993 to 2011, the cumulative balance for the four monitored glaciers has decreased between -10.84 m w.e. (Silver) and -7.34 m w.e. (Sandalee); this translates to a net volume loss of between 9.85M m^3 (North Klawatti) and 1.25M m^3 (Sandalee). The cumulative balances for the four glaciers monitored for this report have declined more slowly than for South Cascade Glacier (Figure 4), which is monitored by the US Geological Survey (USGS), for the same observation period.

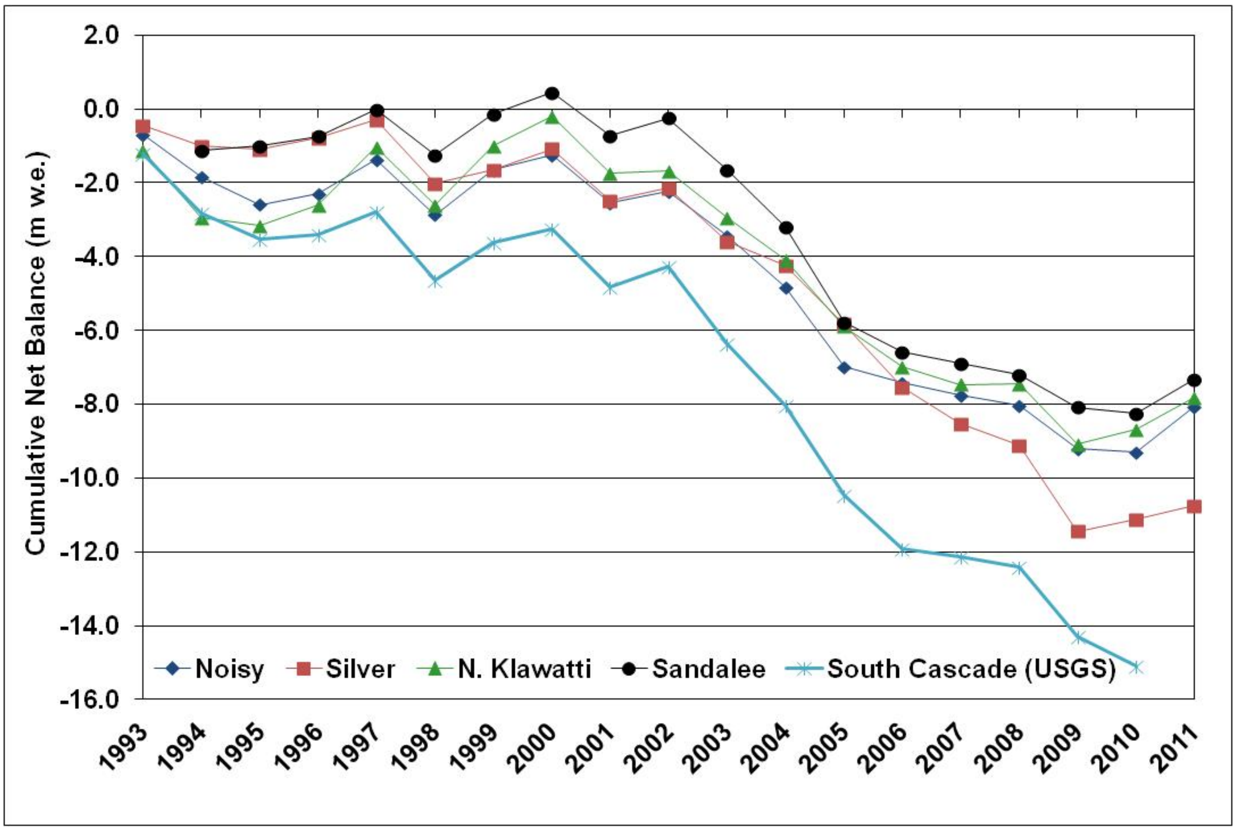

Figure 4. Cumulative balances of four index glaciers at North Cascades National Park Complex for water years 1993-2011, compared to South Cascade Glacier (USGS) for the same time period.

Glacial Contribution to Streamflow

Glacial contribution to runoff was below average in all watersheds during the 2011 summer season due to below average summer melt and a large snowpack in non-glaciated parts of the basins. Glaciers contributed a combined 311M m^3 of meltwater to the four watersheds. The volume of glacial meltwater was the lowest since 1993 in the Baker and Stehekin watersheds and the second lowest in the Thunder and Ross Lake watersheds (Table 3 and Figure 5). The percent of glacial meltwater contributing to summer stream discharge was greatest in Thunder Creek watershed at 22% and lowest in the Ross Lake watershed at 2.5%; approximately 46 to 69% of the 1993-2011 average.

Table 3. Glacial contribution to summer streamflow for four North Cascades National Park Complex watersheds. Meltwater contributions are provided for each index glacier and from all glaciers within the watershed. In parentheses is the percent of total watershed area that is glaciated. Average, minimum and maximum values are calculated from 1993-2011 data (Stehekin 1995-2011).

Site (% area glaciated)	May-September Runoff (million cubic meters)				Percent Glacial of Total Summer Runoff			
	2011	average	min	max	2011	average	min	max
Baker River Watershed								
Noisy Creek Glacier	1.5	1.9	1.5	2.4	---	---	---	---
All glaciers (6%)	102.7	138.3	93.7	170.6	8.6	15.0	8.6	22.7
Thunder Creek Watershed								
North Klawatti Glacier	4.2	4.9	3.4	6.3	---	---	---	---
All glaciers (13%)	87.0	117.9	80.6	144.6	22.0	31.7	20.7	46.1
Stehekin River Watershed								
Sandalee Glacier	0.4	0.6	0.4	0.8	---	---	---	---
All glaciers(3%)	63.2	84.7	58.4	105.7	5.6	10.2	5.6	22.1
Ross Lake Watershed								
Silver Glacier	0.7	1.2	0.6	1.6	---	---	---	---
All glaciers (1%)	57.6	77.3	53.0	96.4	2.5	5.4	2.5	13.0

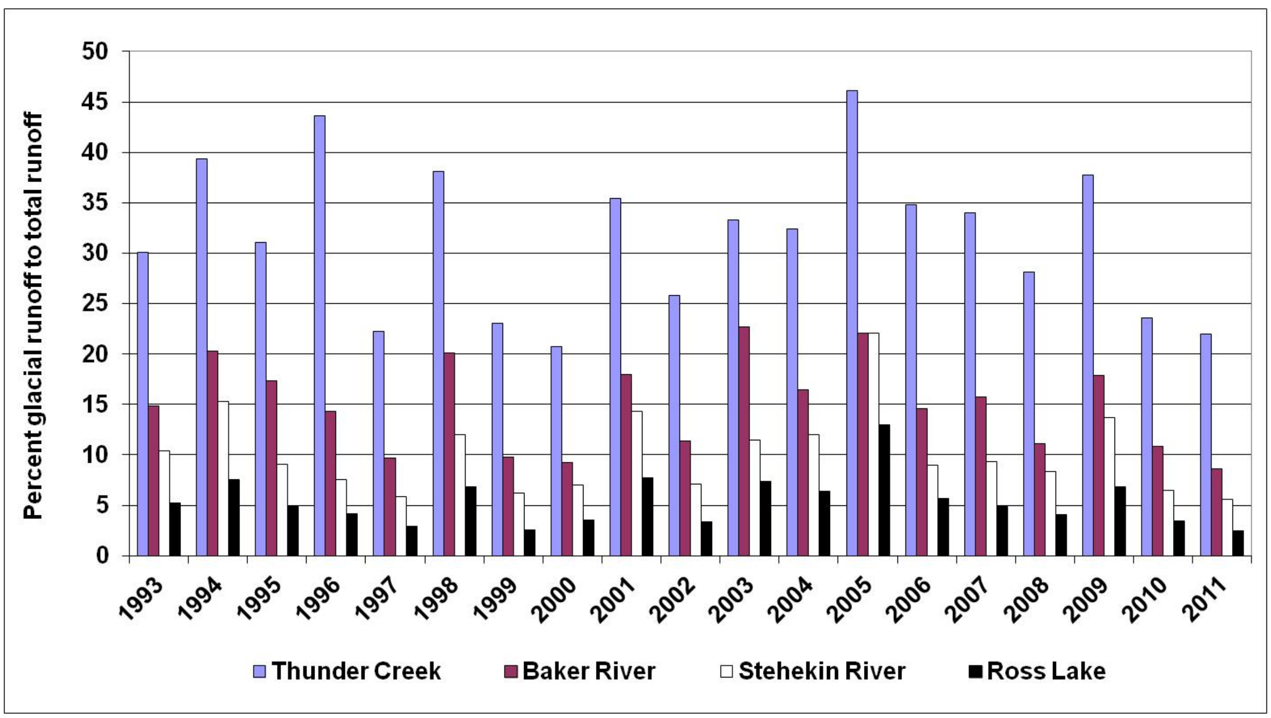

Figure 5. Total summer glacier meltwater contributions for the four watersheds containing glaciers monitored by the North Cascades National Park Complex.

Aerial Imagery

Oblique photographs of each index glacier are shown in Figures 6-9 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.

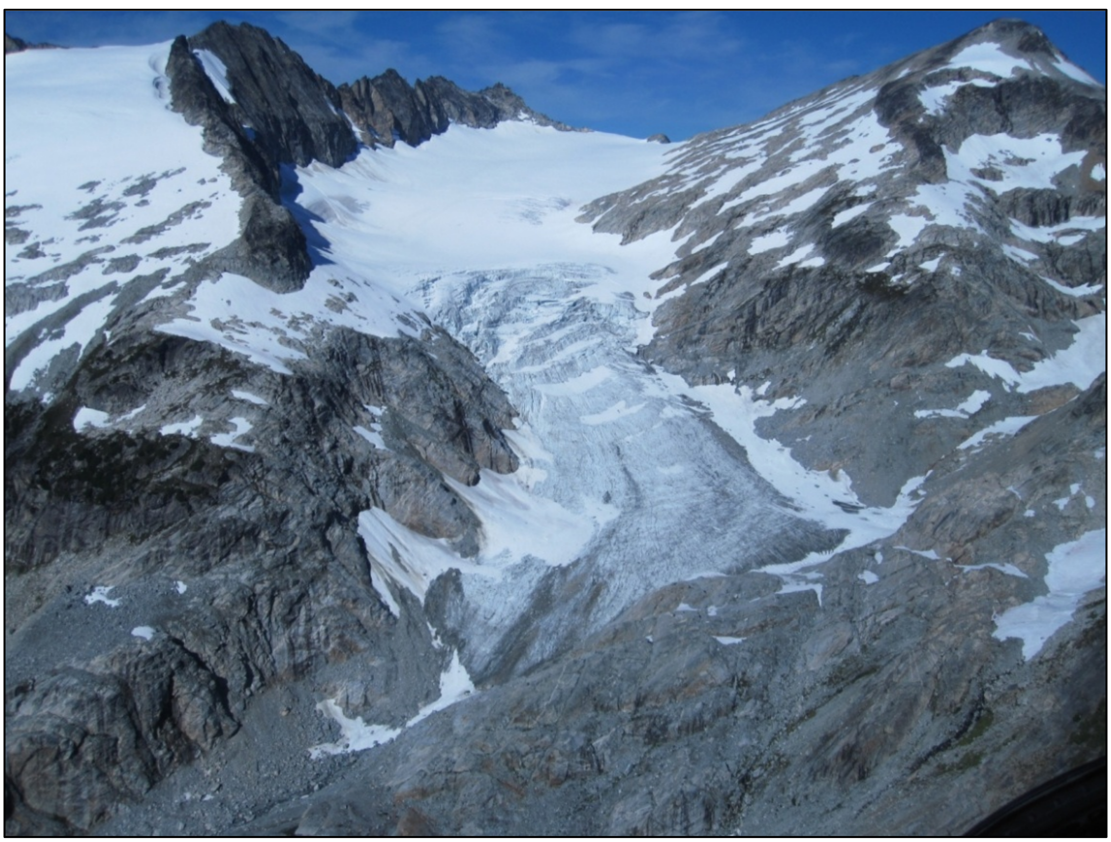

Figure 6. North Klawatti Glacier from east, September 24, 1993 (top) and September 20, 2011 (bottom).

Figure 7. Noisy Glacier from north, September 24, 1993 (top) and September 21, 2011 (bottom).

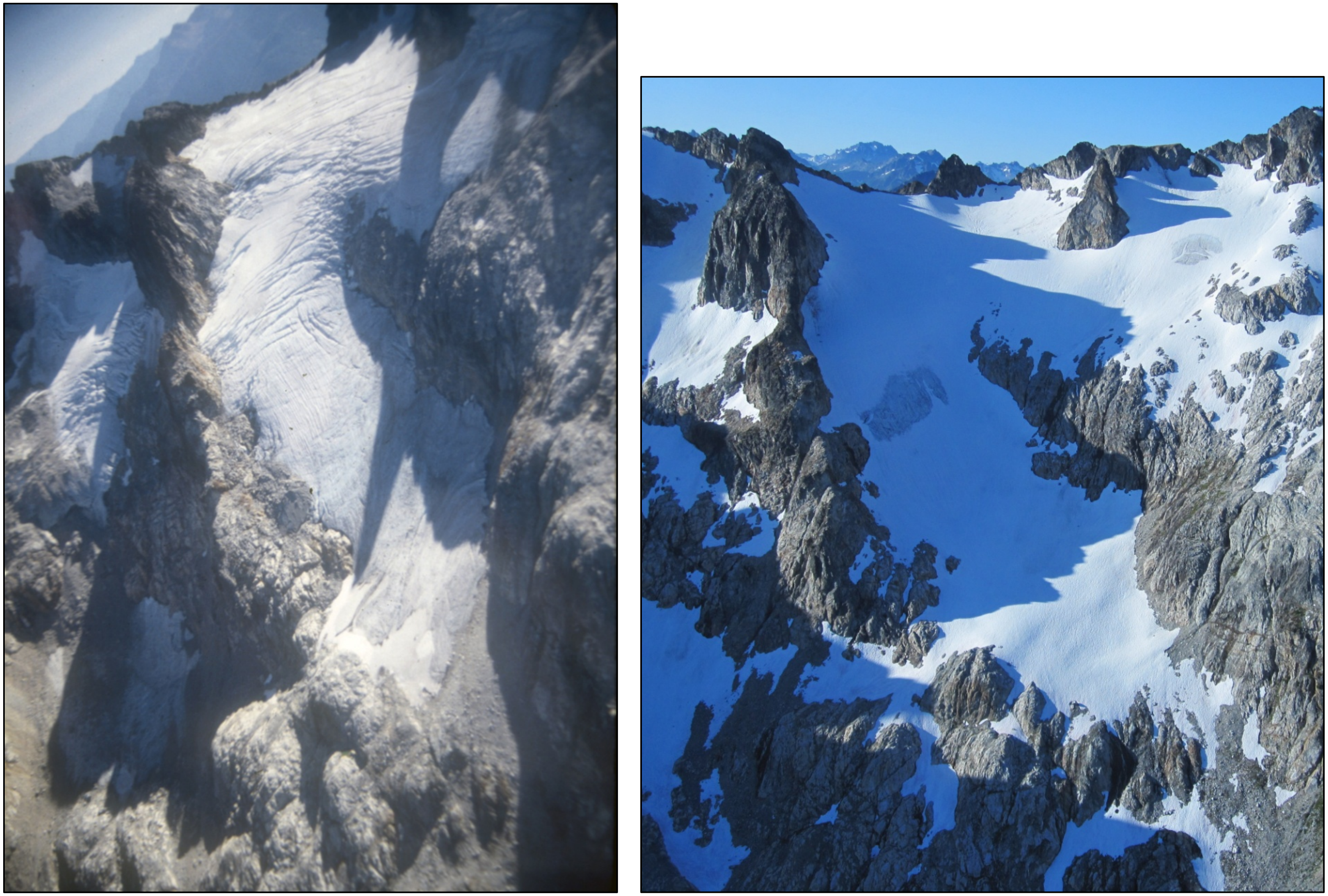

Figure 8. Sandalee Glacier from north, October 3, 1994 (left) and September 20, 2011 (right).

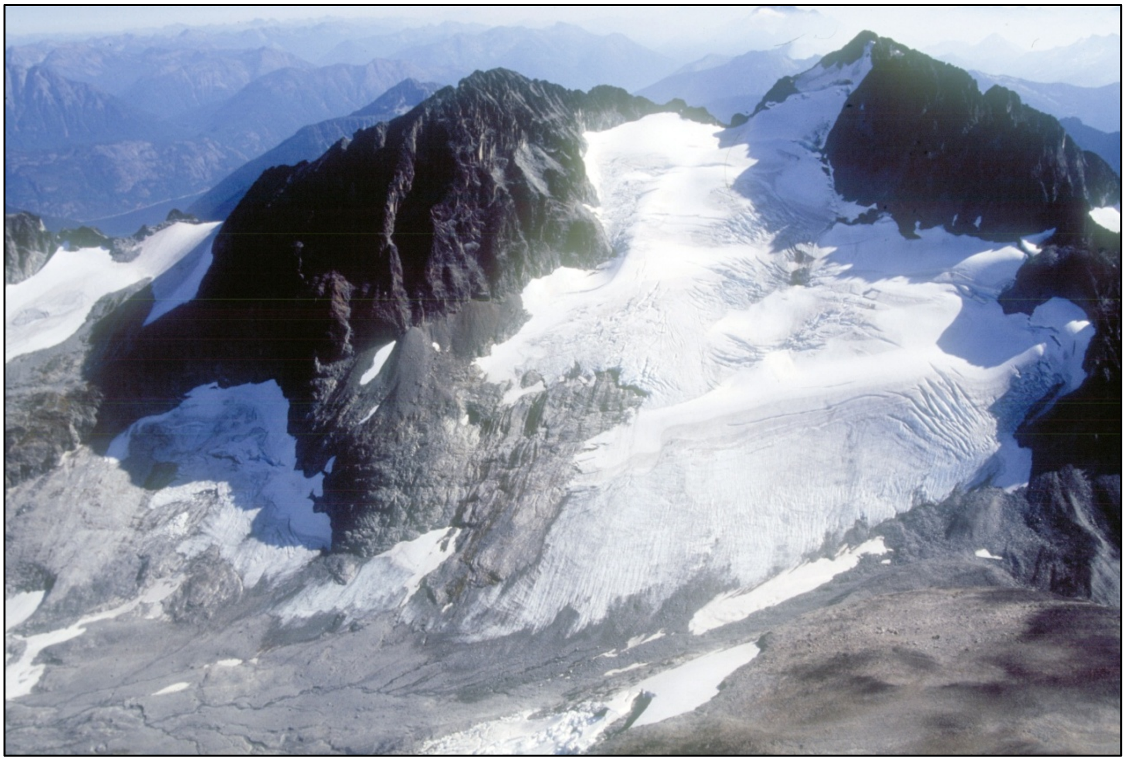

Figure 9. Silver Glacier from north, September 20, 2001 (top) and September 21, 2011 (bottom).

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