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North Cascades National Park Complex Glacier Mass Balance Monitoring Annual Report, Water Year 2013

North Coast and Cascades Network

Natural Resource Data Series NPS/NCCN/NRDS—2018/1142

ON THIS PAGE
Heading back to basecamp from Silver Glacier, summer 2013, North Cascades National Park
Photograph by: North Cascades National Park Complex

ON THE COVER
Noisy Glacier, North Cascades National Park, April 22, 2013
Photograph by: North Cascades National Park Complex

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Abstract

Glaciers cover approximately 93.6 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 (Riedel 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 (Riedel et al, 2008). In this report, glacier monitoring data for water year (WY) 2013 are presented as point mass balance, provisional glacier-wide mass balances and provisional glacier contribution to summer streamflow.

Point mass balances were measured at 18 sites on four glaciers for WY2013. Winter accumulation was near to above average for most sites (96-125 percent of 1993-2012 average), the exception being Silver stake 1 (144%) and North Klawatti stake 5 (81%). Summer balances were above average (106-153 percent of average). Point annual balances were mostly below average ranging from -5.12 to +1.23 meters water equivalent.

Glacier-wide mass balances, which are the integration of point mass balance values across the entire glacier surface were calculated. Winter accumulation was near average at North Klawatti and Sandalee glaciers (101-102%) and above average at Noisy Creek and Silver glaciers (114-131%). Summer melt was above average for all glaciers (111-136%). Glacier-wide annual (net) balances were negative for all glaciers for the first year since 2009 and for the 12th year since 1993.

Glacier contribution to May-September runoff was estimated in four watersheds for WY2013. The volume of glacial runoff was approximately 20 percent above average; contributing an estimated 405 million m^3 of meltwater to streamflow. The percent of glacial contribution to total summer streamflow ranged from 4.7 to 29.2 percent.

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 B. Wright, S. Brady, and S. Dorsch. We want to thank S. Welch, M. Huff, H. Anthony, and J. Oelfke for their administrative support.

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

Annual mass balance: The sum of winter balance (positive) and summer balance (negative), or two successive minima. Annual mass balance is positive if the glacier has gained mass and negative if it has lost mass.

Equilibrium line altitude (ELA): The altitude where annual accumulation and ablation are equal and annual 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.

Glacier-wide mass balance: The mass balance averaged across glacier area. Typically determined from point mass balance measurements integrated across glacier surface.

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

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

Snow bulk density: The density of snow determined by dividing the volume of a sample by its weight.

Snow Telemetry (SNOTEL): Meteorological stations that provide real-time snow and climate data in the mountainous regions of the Western United States using automated remote sensing. They are operated by the Natural Resources Conservation Service.

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 2013 is the 12-month period beginning October 1, 2012 and ending September 30, 2013. 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) 2013, beginning on October 1, 2012 and ending on October 22, 2013.

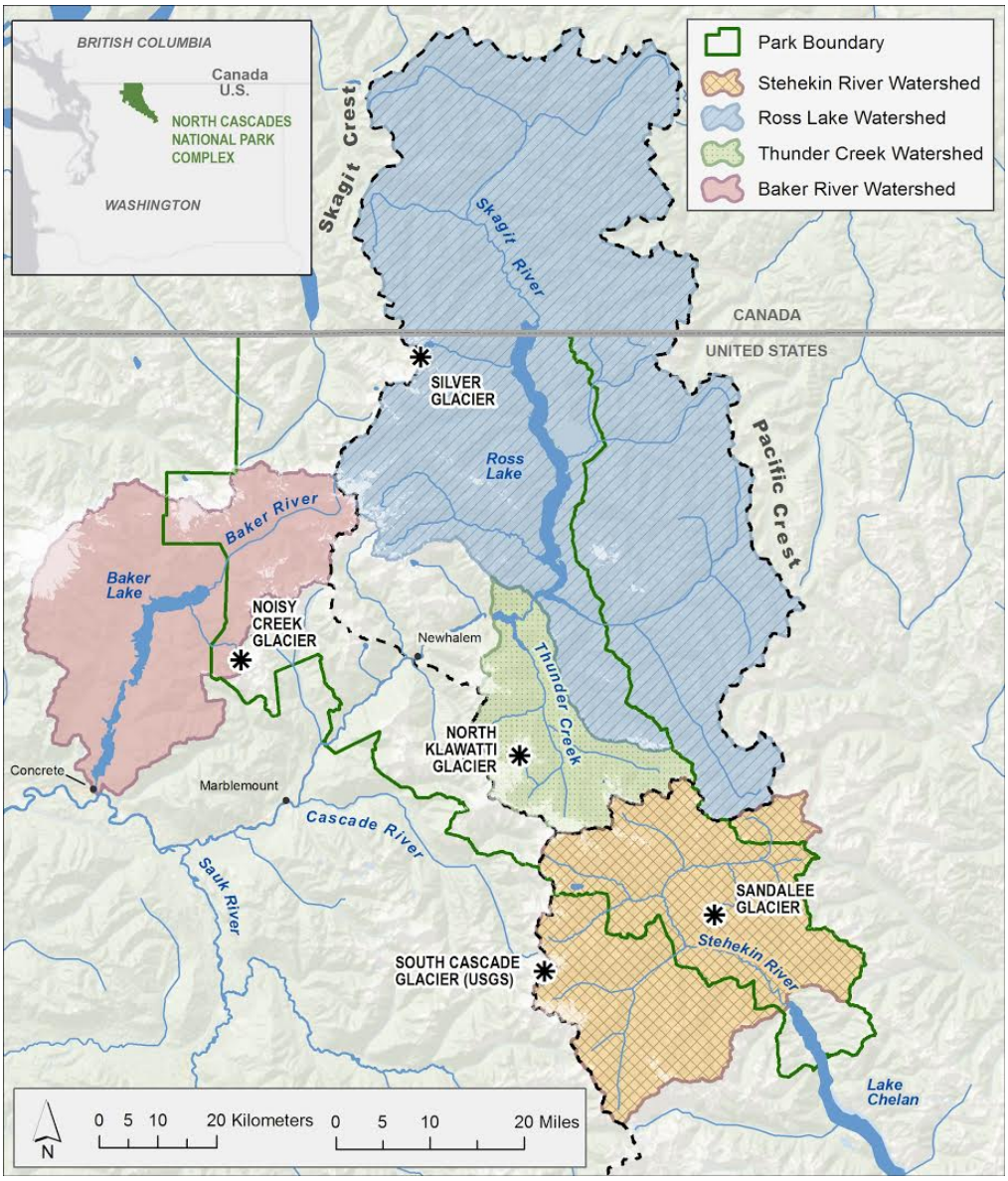

Figure 1. Locations of four glaciers monitored in this study and of the glacier monitored by US Geologic Survey (USGS) within the major hydrologic divides in the North Cascades National Park Complex (Riedel et al. 2008).

Glaciers are a significant resource of the Cascade Range in Washington State. North Cascades National Park contained 312 glaciers that covered 93.56 km^2 in a 2009 inventory (Dick 2013). 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 anthropods (*Collembola;* Hartzell 2003).

Glaciers are also important indicators of regional and global climate change. At NOCA, glacial extent determined from neoglacial moraines, unpublished maps made by from USGS geologist Austin Post in the 1950's, and a 2009 inventory (Dick 2013) indicate that glacier area has declined ~56% in the last 100 years.

The four NOCA index glaciers monitored by the North Coast and Cascades Network (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 annual 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.

Methods

Mass balance measurement methods used in this project are based on procedures established during 55 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 standard operating 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 at fixed points. Integration of the point measurements allows for calculation of the annual (net) mass balance of an entire 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.

Winter balance is calculated from snow depth and bulk density measurements. Snow depth is measured at five to 10 points at 4-5 fixed stations along the centerline of each glacier resulting in 20-50 measurements per glacier. Snow bulk density is routinely 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 is used. This value is also compared to values measured independently at snow telemetry (SNOTEL) 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 to measure the depth of winter accumulation. 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).

Occasionally, snowpack conditions result in fewer than 5 measurements per station. Commonly this is due to the depth of the snowpack exceeding the length of the snow probes, difficult probing conditions or the previous summer surface was uncertain. When this occurs, reconstructions of snow depth are determined by summing measurements of snow depths collected during a subsequent site visit with melt observed at stakes since the original spring visit.

In WY2013, fall data collection was postponed due to a federal government closure. Combined with early onset of snow, this resulted in a combined five stakes at three glaciers not being recovered. Therefore, the summer ablation values were estimated. Summer melt for Silver stake 1, and Sandalee stakes 1 & 2, were estimated by calculating the ratio of spring to summer melt in 2013 with adjacent stakes and applying the same ratio to calculate summer to fall melt. For North Klawatti stake 1 & 2,

no summer trip occurred in 2013; therefore melt was estimated using a period of record melt ratio between adjacent stakes.

Seasonal balances from 2013 were compared to the period record average, 1993-2012 for Noisy, North Klawatti, and Silver glaciers, and 1995-2012 for Sandalee Glacier. Previous period of records are found in Riedel and Larrabee (2017).

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.

Point mass balances are direct field measurements of winter accumulation and summer melt at one location. For both winter and summer balances, the measurement points are typically located at ablation stakes sites. For a single glacier there are 4-5 sites corresponding with the number of ablation stakes (Figures 2-5).

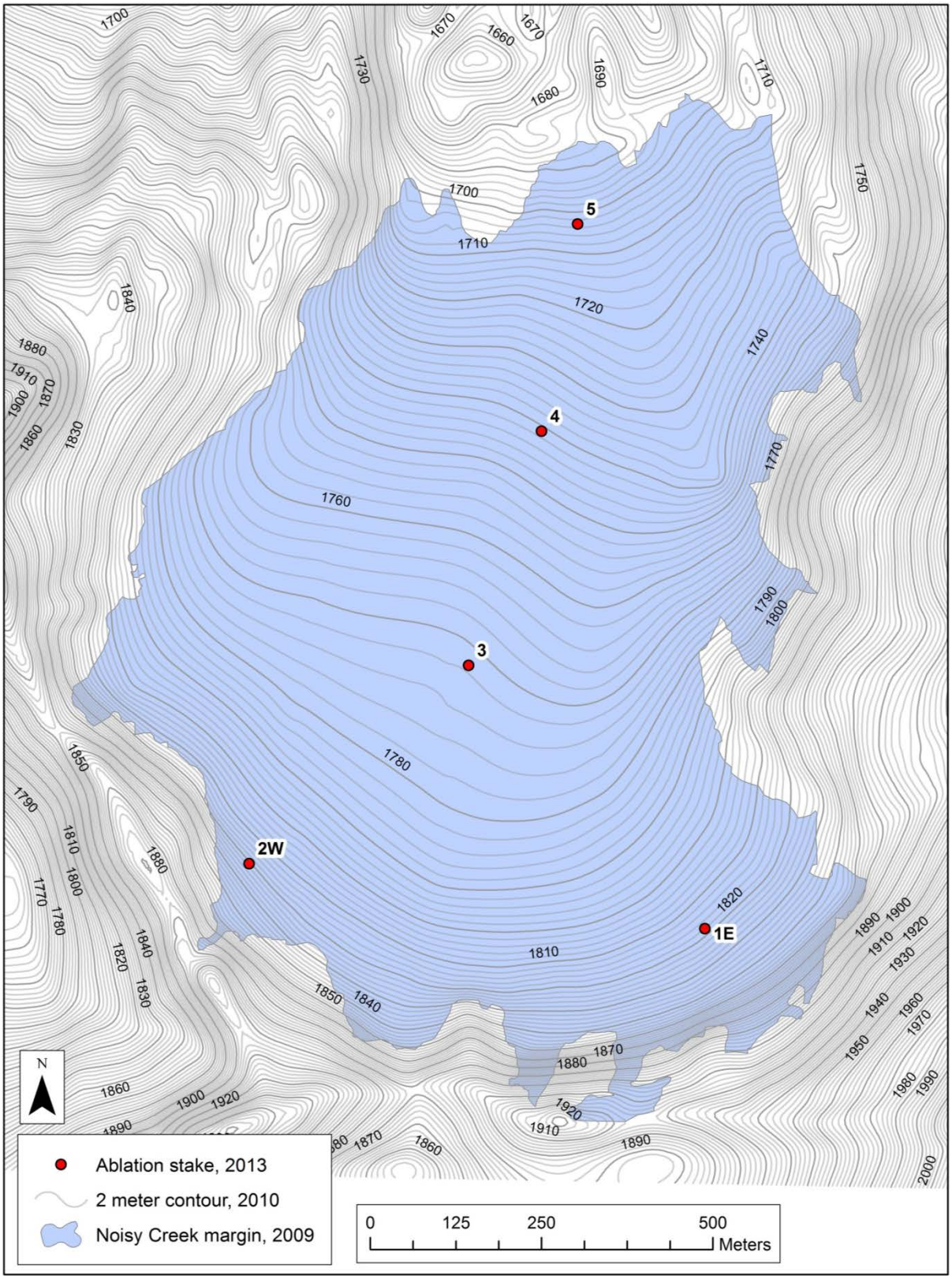

Figure 2. Noisy Creek Glacier with locations of 2013 ablation stakes.

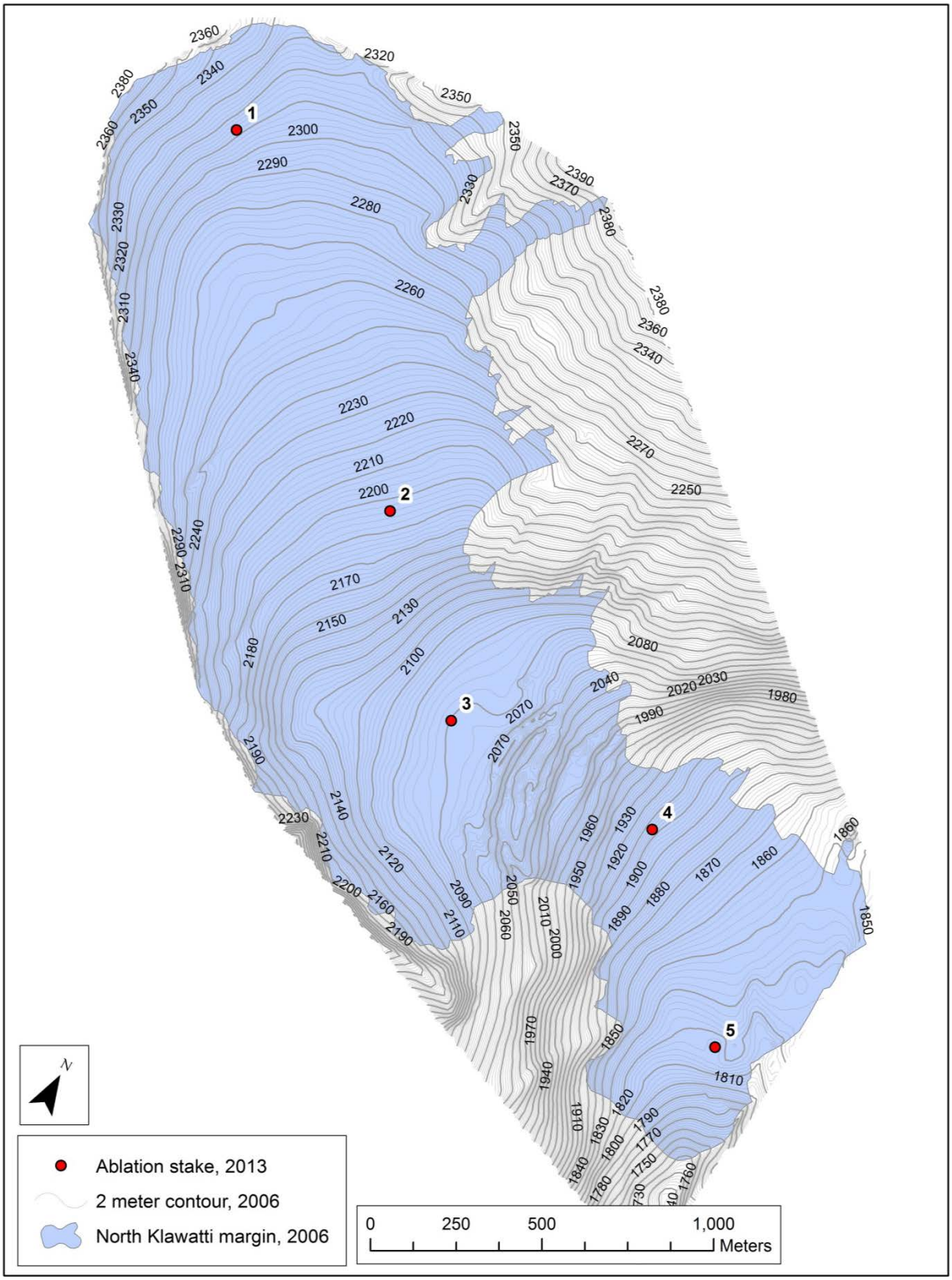

Figure 3. North Klawatti Glacier with locations of 2013 ablation stakes.

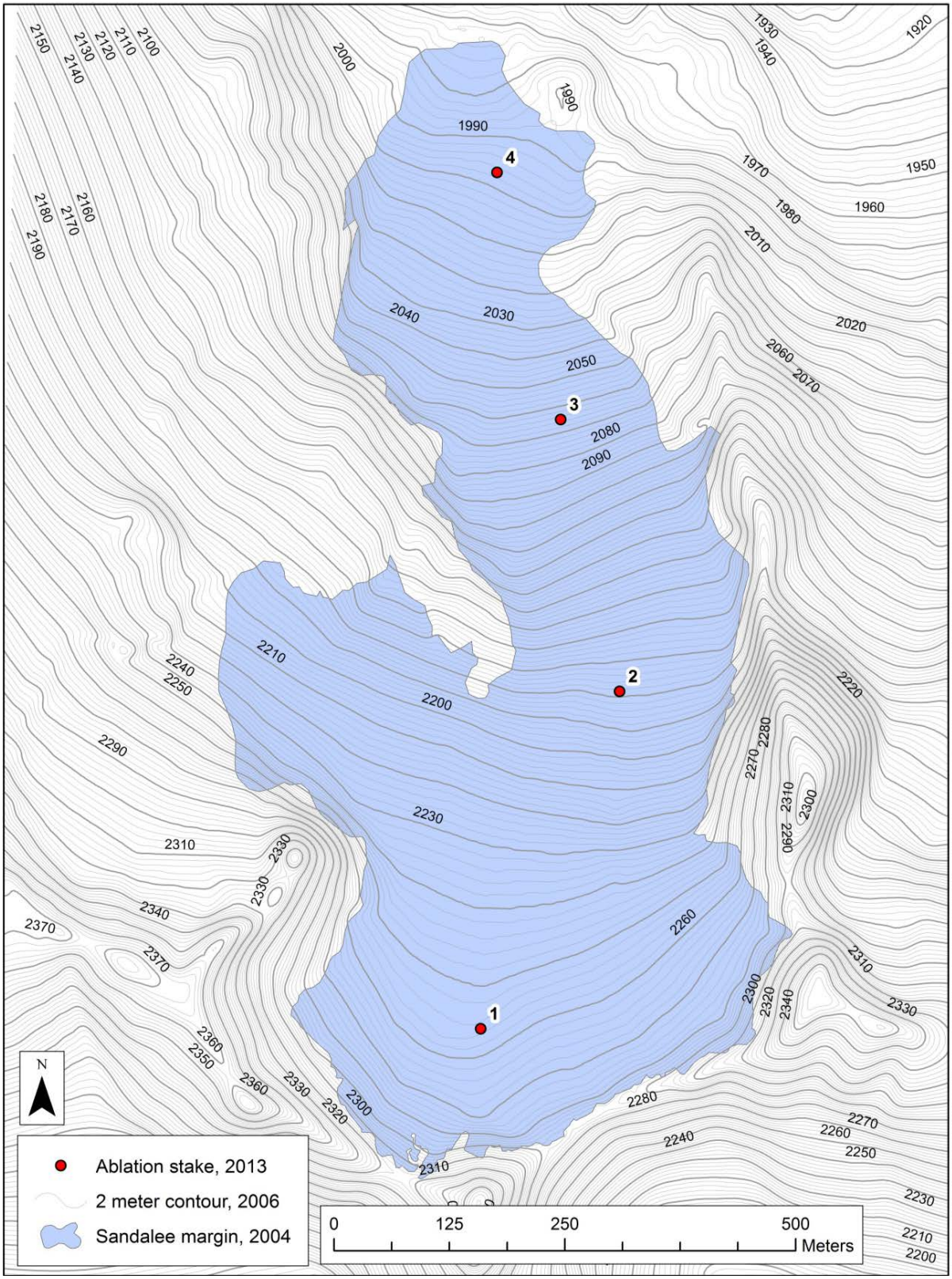

Figure 4. Sandalee Glacier with locations of 2013 ablation stakes.

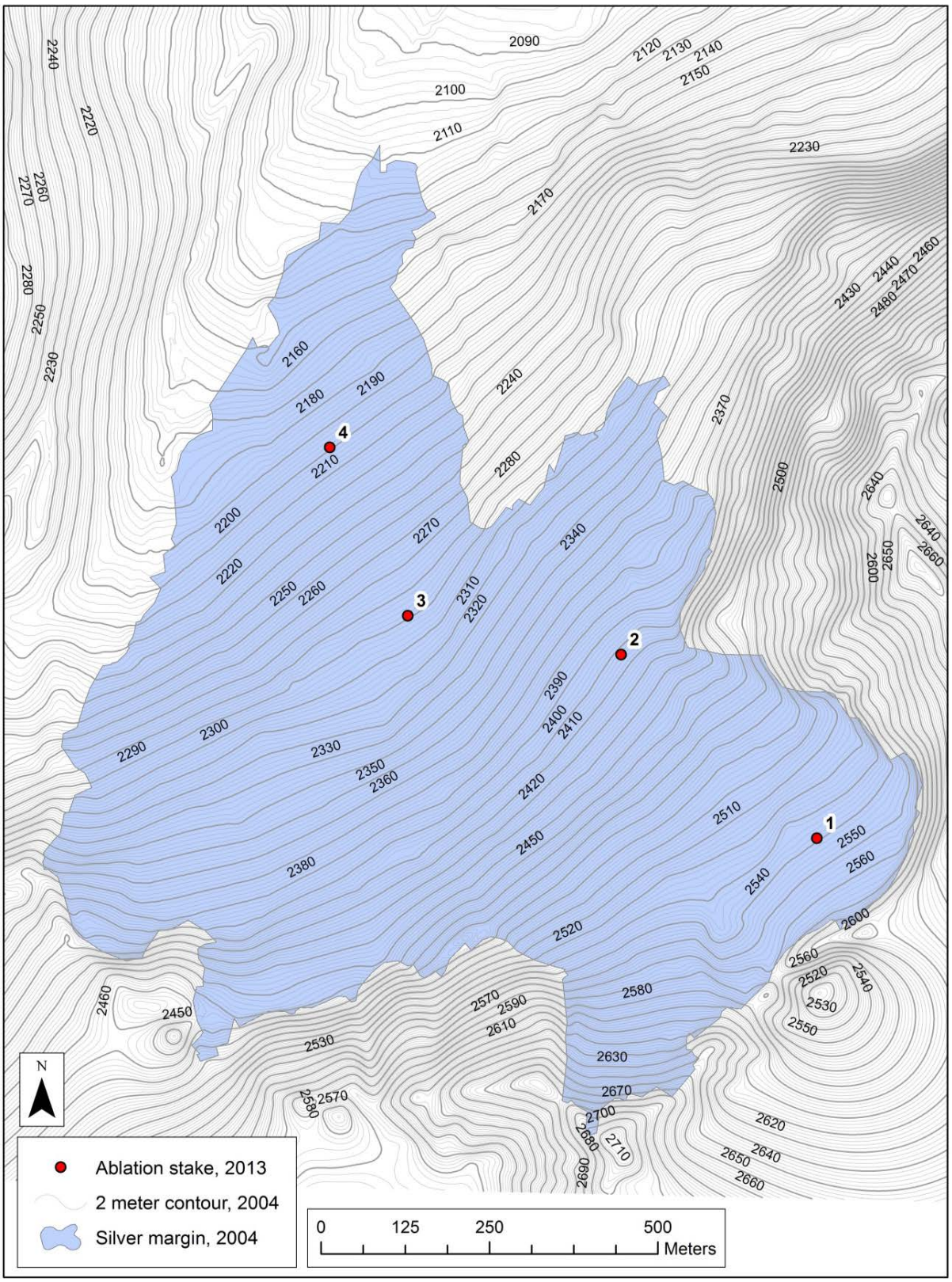

Figure 5. Silver Glacier with locations of 2013 ablation stakes.

Glacier Reference Maps

Glacier-wide mass balances are the integration of point mass balance values across the entire glacier surface using area and altitude data taken from base maps. These estimates are necessary to understand glacial meltwater production. Accurate glacier maps are integral to glacier-wide mass balance calculations. 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 (Table 1). 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. New base maps will be completed in 2017.

Table 1. Map years of glacier margin and contour data used for glacier-wide mass balances calculations in this report.

Monitoring years (WY)	Noisy Creek		N. Klawatti		Silver		Sandalee	
	Margin	Contour	Margin	Contour	Margin	Contour	Margin	Contour
1993-1999	1993	1993	1993	1993	1993	1993	1996	1996
2000-2013	2009	2010	2006	2006	2004	2004/2005	2004	2006

Glacier 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 (Riedel and Larrabee 2016). 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.

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 annual balance estimates in WY 2013 were a mix of above and below period of record average values (POR; Table 2). North Klawatti Glacier was the only glacier with below average error for all balances. Annual balance error on Silver Glacier was the highest of all four glaciers at ±0.44 m water equivalent (w.e.).

Table 2. Calculated error in meters water equivalent (m w.e.) for water year 2013 mass balance calculations for NOCA index glaciers, with period of record (1993-2012) averages in parentheses.

	Average Stake Error (m w.e.)		
Glacier	**Winter Balance**	**Summer Balance**	**Annual Balance**
Noisy Creek	±0.17 (0.21)	±0.27 (0.26)	±0.33 (0.33)
North Klawatti	±0.19 (0.20)	±0.29 (0.31)	±0.35 (0.36)
Sandalee	±0.25 (0.21)	±0.28 (0.28)	±0.37 (0.36)
Silver	±0.27 (0.21)	±0.34 (0.29)	±0.44 (0.36)

Data Quality and Completeness

Winter snow accumulation (henceforth accumulation) was measured on April 22nd at Noisy Creek and Sandalee glaciers and May 7th for North Klawatti and Silver glaciers. The gap in timing was due to poor weather conditions not suitable for safe access to field sites. Snow bulk density measured at Noisy Creek Glacier stake 3 was 0.54. The regional average springtime snow density of 0.5 was used at Silver and North Klawatti glaciers. For Sandalee Glacier, the period of record average density of 0.44 was used.

At several stations, difficult probing conditions and weak summer surface development resulted in fewer than the minimum 5 measurements per station as required by our monitoring protocol. For Sandalee stakes 2 and 4 and Silver stakes 1-3, reconstructions of winter accumulation using summer probe values and observed melt were made (Table 3).

Stakes on Silver and Sandalee were placed in new locations. At stake 3 on Sandalee Glacier, avalanche conditions prompted the movement of the stake 20 meters northwest, to less steep slopes. At Stake 2 on Silver, GPS difficulties and time constraints lead to the stake being placed 20 meters north, at a lower elevation than normal. These adjustments are necessary as the glaciers change.

Mid-season field visits as a check on winter accumulation and early summer melt occurred between July 3rd and July 17th for Noisy, Sandalee and Silver glaciers. No mid-season field visit occurred for North Klawatti Glacier. Final summer ablation measurements were collected on September 26th for

Noisy and Silver and October 22nd for North Klawatti and Sandalee glaciers. The gap in timing was due to poor weather conditions and a 16 day federal government closure in 2013. Significant snow accumulations occurred prior to fall visits, with new snow depth of nearly one meter at some stakes. The introduction of 'political error' resulted in a number of stakes unrecovered in the fall because they were buried by snow; therefore summer melt was estimated at several stakes. Methods for estimating melt are described in the Methods section of this report.

Table 3. WY2013 spring snow depth (winter accumulation) measurements for four index glaciers monitored at North Cascades National Park Complex. Stake elevations based on 2004, 2006 & 2010 reference maps. Average, minimum and maximum values calculated from a series of measurements at each stake. Units are in meters (m).

Glacier	Stake ID	Stake Elevation[a] (m)	Date	WY2013 Average (m)	Min. (m)	Max. (m)	Difference (m)	Std. Dev. (m)
Noisy	1E	1818	4/22	6.74	6.49	7.24	0.75	0.43
Noisy	2W	1820	4/22	7.89	7.60	8.10	0.50	0.21
Noisy	3	1772	4/22	6.33	6.23	6.43	0.20	0.09
Noisy	4	1740	4/22	6.15	6.05	6.25	0.20	0.08
Noisy	5	1704	4/22	6.08	5.95	6.32	0.37	0.12
N. Klawatti	1	2312	5/7	6.25	5.77	6.72	0.95	0.32
N. Klawatti	2	2196	5/7	6.06	5.77	6.33	0.56	0.21
N. Klawatti	3	2080	5/7	6.25	6.21	6.31	0.10	0.04
N. Klawatti	4	1916	5/7	5.06	4.68	5.56	0.88	0.31
N. Klawatti	5	1826	5/7	3.82	3.61	4.09	0.48	0.18
Sandalee	1	2538	4/22	6.00	5.94	6.05	0.11	0.06
Sandalee	2	2402	4/22	6.64[b]	6.12[b]	7.27[b]	1.15	0.47
Sandalee	3	2288	4/22	6.25	5.93	6.65	0.72	0.29
Sandalee	4	2198	4/22	7.64[b]	7.16[b]	8.45[b]	1.29	0.36
Silver	1	2254	5/7	7.42[b]	6.79[b]	7.95[b]	1.16	0.42
Silver	2	2178	5/7	5.61[b]	5.22[b]	6.30[b]	1.08	0.39
Silver	3	2066	5/7	6.48[b]	4.94[b]	7.75[b]	2.81	0.83
Silver	4	1996	5/7	3.79	2.72	4.54	1.82	0.64

[a] Elevations determined from XY locations on glacier digital elevation models (DEMs). Map years used: Noisy Creek Glacier = 2010; N. Klawatti = 2006; Sandalee = 2006; Silver = 2004.

[b] Reconstructed from summer or fall snow depth values and stake melt.

Point Mass Balances

Winter accumulation was near or above the POR average for most sites (96-125%), the exception being the highest elevation stake at Silver stake 1 (144%) and the lowest at North Klawatti stake 5 (81%; Tables 3 and 4, Figures 6 and 7). The deepest snowpacks were generally located in sites with known sources of secondary accumulation from wind or avalanching, including Noisy 2W, Sandalee 4 and Silver 3. The summer balances were above the POR average, ranging between 106-153 percent of average. Point annual balances were mostly below the POR average, ranging from -5.12 to +1.23 m w.e. Only 4 of 18 stakes had positive annual balances and this was generally occurred at higher elevation, more western sites. All stakes on Noisy Creek Glacier had negative annual balances due to the glaciers relatively low elevation.

Table 4. WY2013 point balances measurements for four index glaciers monitored at North Cascades National Park Complex. Units are in meters (m) and meters water equivalent (m w.e.). Period of record (POR) average is calculated from 1993-2012 data (Sandalee 1995-2012). Stake elevations based on 2004/ 2006/ 2010 reference maps.

			Winter Balances (m w.e.)		Summer Balances (m w.e.)		Annual Balances (m w.e.)	
Glacier	**Stake ID**	**Stake Elevation[a] (m)**	**2013**	**POR Average**	**2013**	**POR Average**	**2013**	**POR Average**
Noisy Creek	1E	1818	3.64	3.41	-4.48	-3.54	-0.84	-0.14
	2W	1820	4.26	3.46	-4.45	-3.48	-0.18	-0.02
	3	1772	3.42	3.07	-4.03	-3.12	-0.61	-0.04
	4	1740	3.32	2.88	-4.33	-3.61	-1.01	-0.73
	5	1704	3.28	2.94	-4.53	-3.84	-1.25	-0.90
North Klawatti	1	2312	3.12	2.95	-2.61[c]	-2.46	0.51	0.50
	2	2196	3.03	3.08	-2.92[c]	-2.75	0.11	0.34
	3	2080	3.13	3.10	-3.46	-3.23	-0.33	-0.14
	4	1916	2.53	2.62	-6.12	-4.79	-3.59	-2.17
	5	1826	1.91	2.36	-7.03	-5.15	-5.12	-2.79
Sandalee	1	2254	2.64[b]	2.59	-2.83[c]	-2.52	-0.19	0.06
	2	2178	2.92	2.81	-2.93	-2.63	-0.01	0.18
	3	2066	2.75[b]	2.59	-3.54	-3.32	-0.79	-0.72
	4	1996	3.36	3.19	-3.77	-3.48	-0.41	-0.30
Silver	1	2538	3.71[b]	2.58	-2.48[c]	-1.62	1.23	0.95
	2	2402	2.80[b]	2.21	-3.09	-2.27	-0.28	-0.06
	3	2288	3.24[b]	2.67	-2.90	-2.33	0.34	0.34
	4	2198	1.89	1.52	-4.56	-3.21	-2.66	-1.69

[a] Elevations determined from XY locations on geodetic maps. Map years used: Noisy Creek Glacier = 2010; N. Klawatti = 2006; Sandalee = 2006; Silver = 2004.

[b] Reconstructed from summer or fall snow depth values and stake melt.

[c] Estimated values

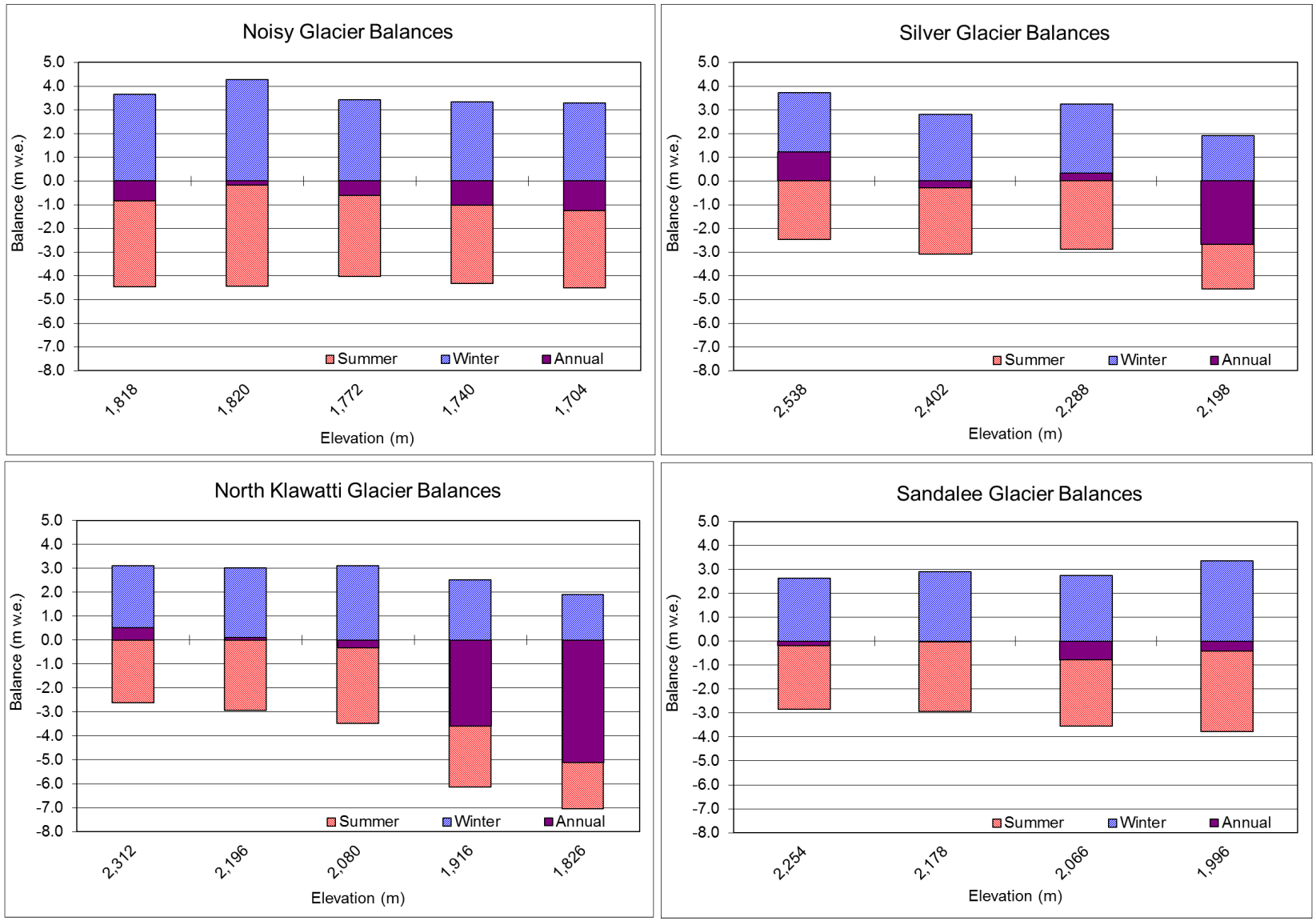

Figure 6. Seasonal and annual point mass balances of four North Cascades National Park Complex index glaciers for water year 2013. Units are in meters water equivalent (m w.e.).

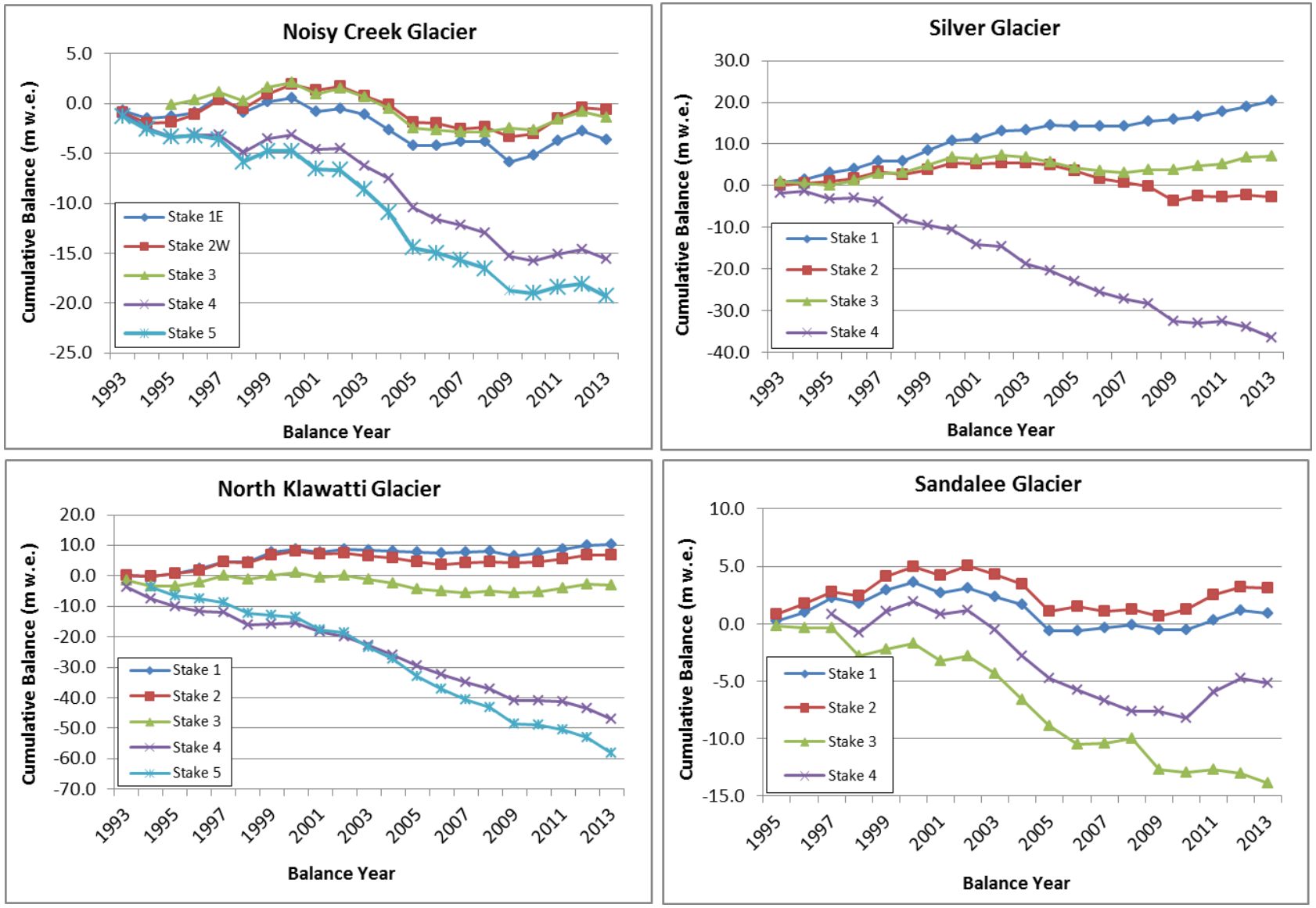

Figure 7. Cumulative point annual (net) mass balances for each of four index glaciers at North Cascades National Park Complex for water years 1993-2013. Units are in meters water equivalent (m w.e.).

Glacier-wide Mass Balances

Glacier-wide winter accumulation was near the POR average for North Klawatti and Sandalee glaciers (101 and 102% respectively) and above the POR average for Noisy Creek and Silver glaciers (114 and 131% respectively). Winter balances were the fifth greatest at Silver Glacier and sixth greatest at Noisy Creek Glacier since 1993. Summer melt in WY2013 was above the POR average at all glaciers, balances ranged from 111 to 136 percent of average (Sandalee and Silver respectively). Summer balance at Noisy Creek was its second most negative since 1993, the remaining index glaciers ranked between fourth and sixth most negative for their respective record. Glacier-wide annual mass balances in WY2013 were negative for all four glaciers. This was first year since 2009 with negative annual balances for all four glaciers and the 12th year since 1993. Glacier-wide balances are presented in Table 5 and Figures 8-10.

Table 5. Provisional WY2013 glacier-wide mass balances and equilibrium line altitudes (ELA) for four index glaciers monitored at North Cascades National Park Complex. Average values are calculated from 1993-2012 data (Stehekin 1995-2012). Units are in meters water equivalent (m w.e.), meters (m) and million cubic meters (million m^3). Period of record (POR) average is calculated from 1993-2012 data (Sandalee 1995-2012). Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

	Winter Balance (m w.e.)		**Summer Balance (m w.e.)**		**Annual Balance (m w.e.)**		**ELA (m)**		**Volume change (million m^3)**	
Glacier	**2013**	**POR Average**	**2013**	**POR Average**	**2013**	**POR Average**	**2013**	**POR Average**	**2013**	**POR Cumulative**
Noisy Cr.	3.52	3.11	-4.30	-3.49	-0.77	-0.38	1885	1835	-0.41	-3.79
N. Klawatti	2.91	2.89	-3.78	-3.36	-0.87	-0.47	2200	2167	-1.29	-11.57
Sandalee	2.86	2.81	-3.10	-2.80	-0.29	-0.14	2325	2178	-0.06	-1.05
Silver	2.89	2.24	-3.25	-2.42	-0.36	-0.18	2390	2367	-0.17	-3.34

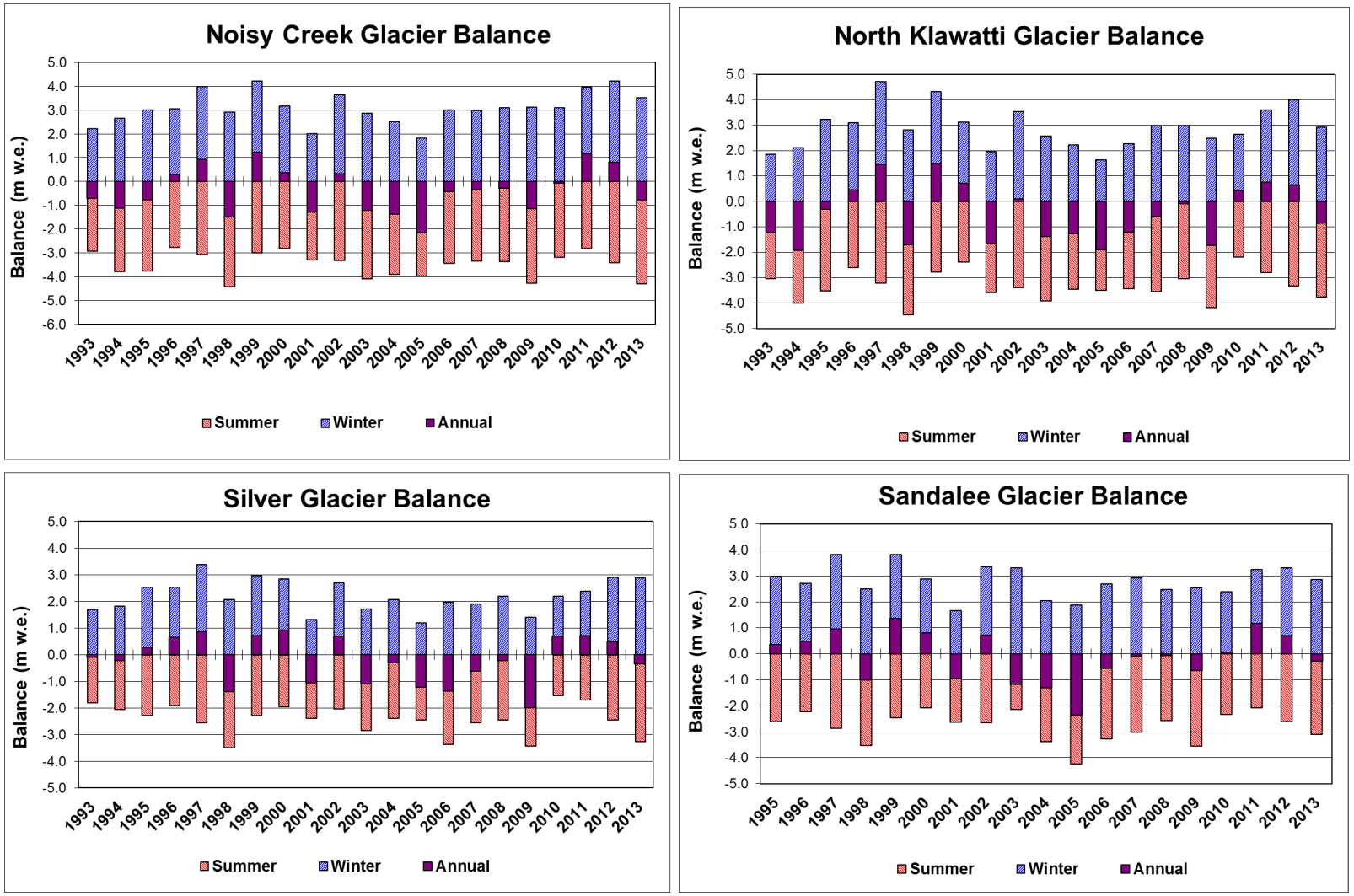

Figure 8. Provisional winter, summer and annual mass balances of four North Cascades National Park Complex index glaciers for water years 1993-2013. Units are in meters water equivalent (m w.e.). Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

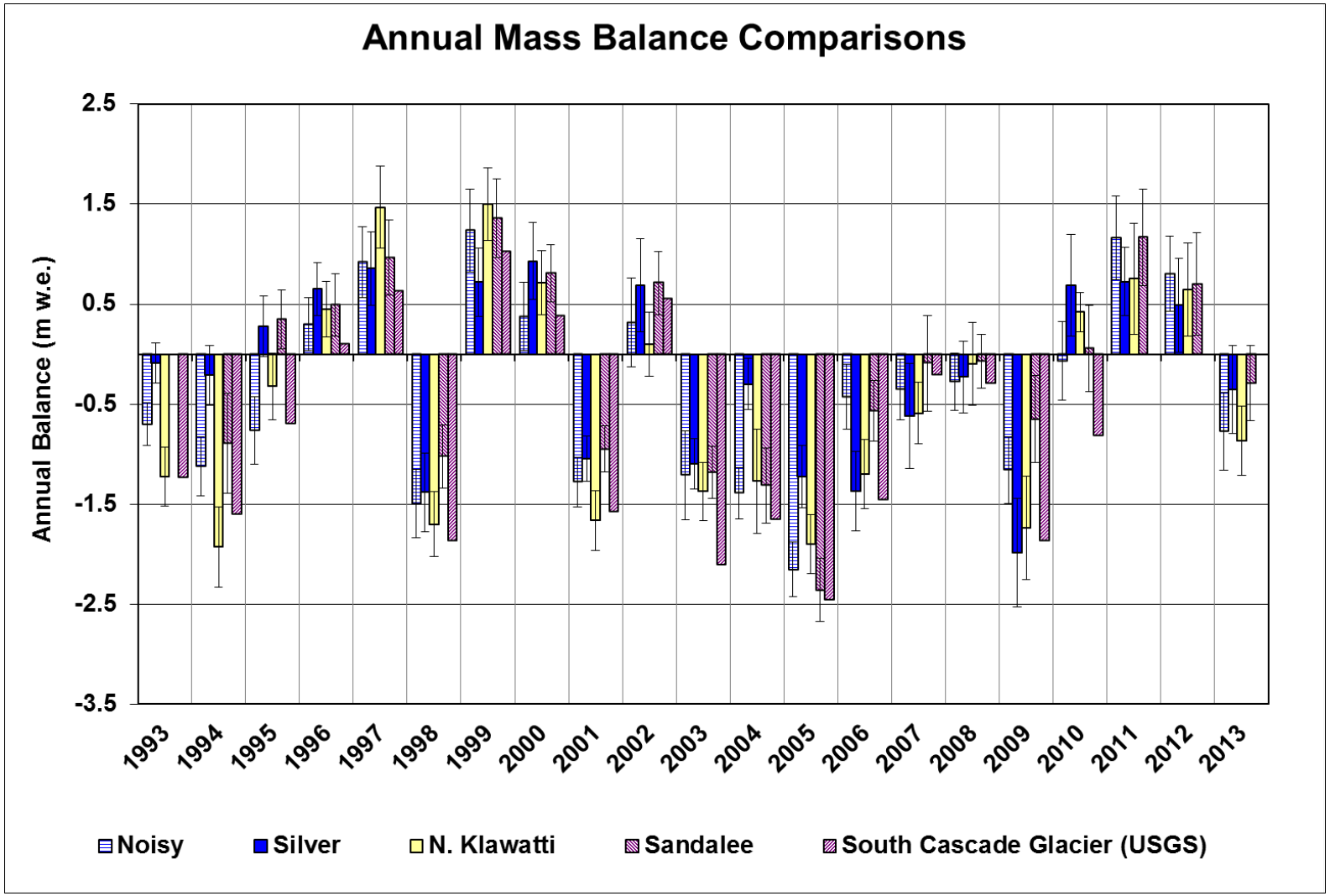

Figure 9. Provisional glacier-wide annual mass balances for each glacier of four index glaciers at North Cascades National Park Complex for water years 1993-2013, compared to South Cascade Glacier (USGS) for the 1993-2010. Units are in meters water equivalent (m w.e.). Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

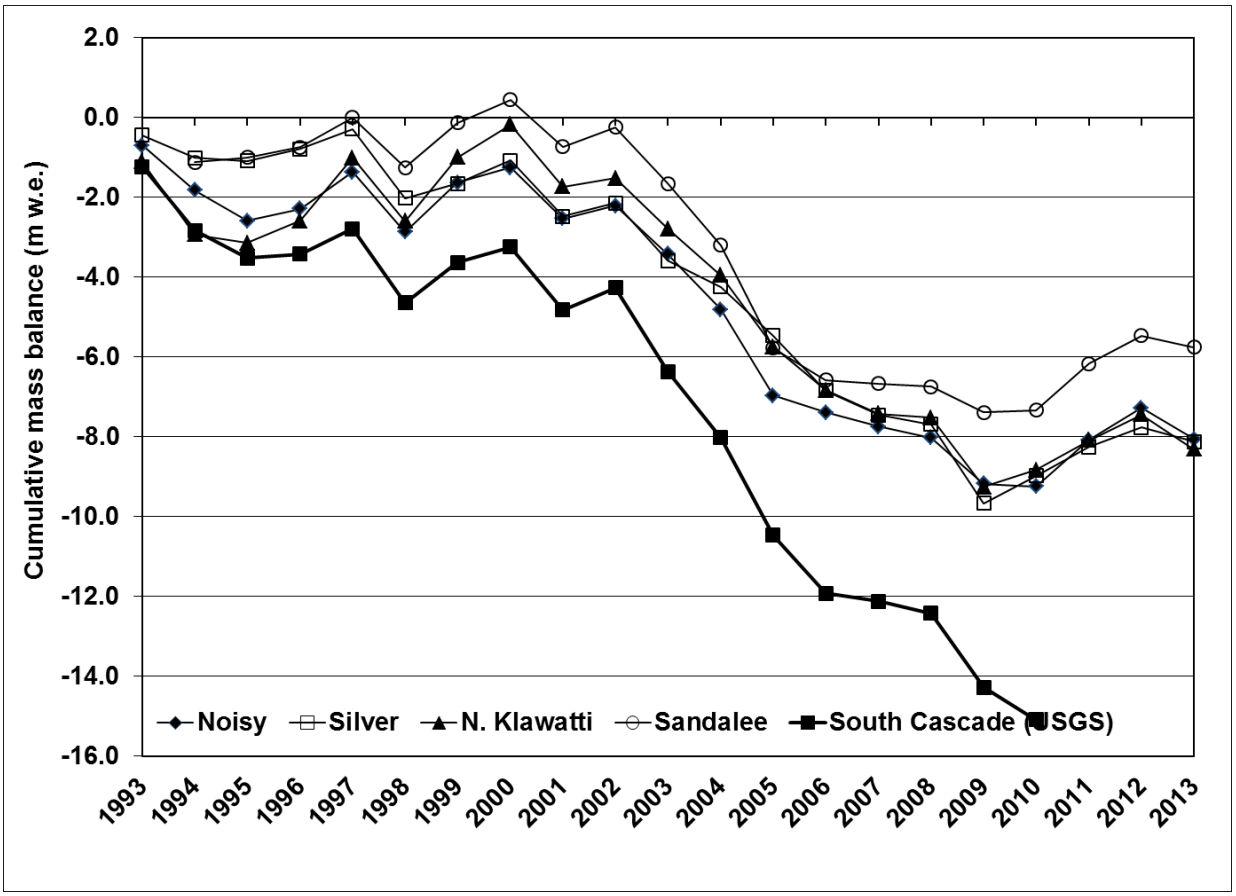

Figure 10. Provisional cumulative balances of four index glaciers at North Cascades National Park Complex for water years 1993-2013, compared to South Cascade Glacier (USGS) for 1993-2010. Units are in meters water equivalent (m w.e.). Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

Glacier Contribution to Streamflow

The volume of glacial runoff originating from all glaciers was approximately 20 percent above the POR average in four NOCA watersheds in summer 2013 due to above average summer melt. Glaciers contributed an estimated 405 million m^3 (107 billion gallons) of meltwater to streamflow (Table 6 and Figure 11). Glacial meltwater as a percent of the total summer streamflow ranged from 4.7 to 29.2 percent, with Thunder and Stehekin watersheds modestly above average and Baker and Ross Lake modestly below the POR average. Glacier recession in the Skagit watershed in the last 50 years has resulted in significant declines in glacier contributions to summer base flows. In relatively warm dry years, glacier contributions have declined by 25 percent between 1959 and 2009 (Riedel and Larrabee 2016).

Table 6. Provisional glacial contribution to summer streamflow for four North Cascades National Park Complex watersheds for water year 2013. 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. Period of average (POR) average, minimum and maximum values are calculated from 1993-2012 data (Stehekin 1995-2012). Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

		May-September Runoff (million cubic meters)				**Percent Glacial of Total Summer Runoff**			
Watershed	**Site (% area glaciated)**	**2013**	**POR average**	**POR min.**	**POR max.**	**2013**	**POR average**	**POR min.**	**POR max.**
Baker River	Noisy Cr.	1.7	1.7	1.3	2.4	–	–	–	–
	All glaciers (4.1%)	126.2	104.7	72.0	132.2	9.7	11.2	6.7	17.2
Thunder Creek	N. Klawatti	5.3	4.8	3.1	6.7	–	–	–	–
	All glaciers (12.2%)	120.6	99.9	70.4	127.2	29.2	26.6	17.4	40.6
Stehekin River	Sandalee	0.6	0.5	0.4	0.8	–	–	–	–
	All glaciers (2.4%)	72.5	60.2	42.3	76.6	7.9	7.1	4.1	15.8
Ross Lake	Silver	1.3	1.0	0.6	1.7	–	–	–	–
	All glaciers (0.8%)	86.1	72.0	49.7	91.4	4.7	5.0	2.3	12.3

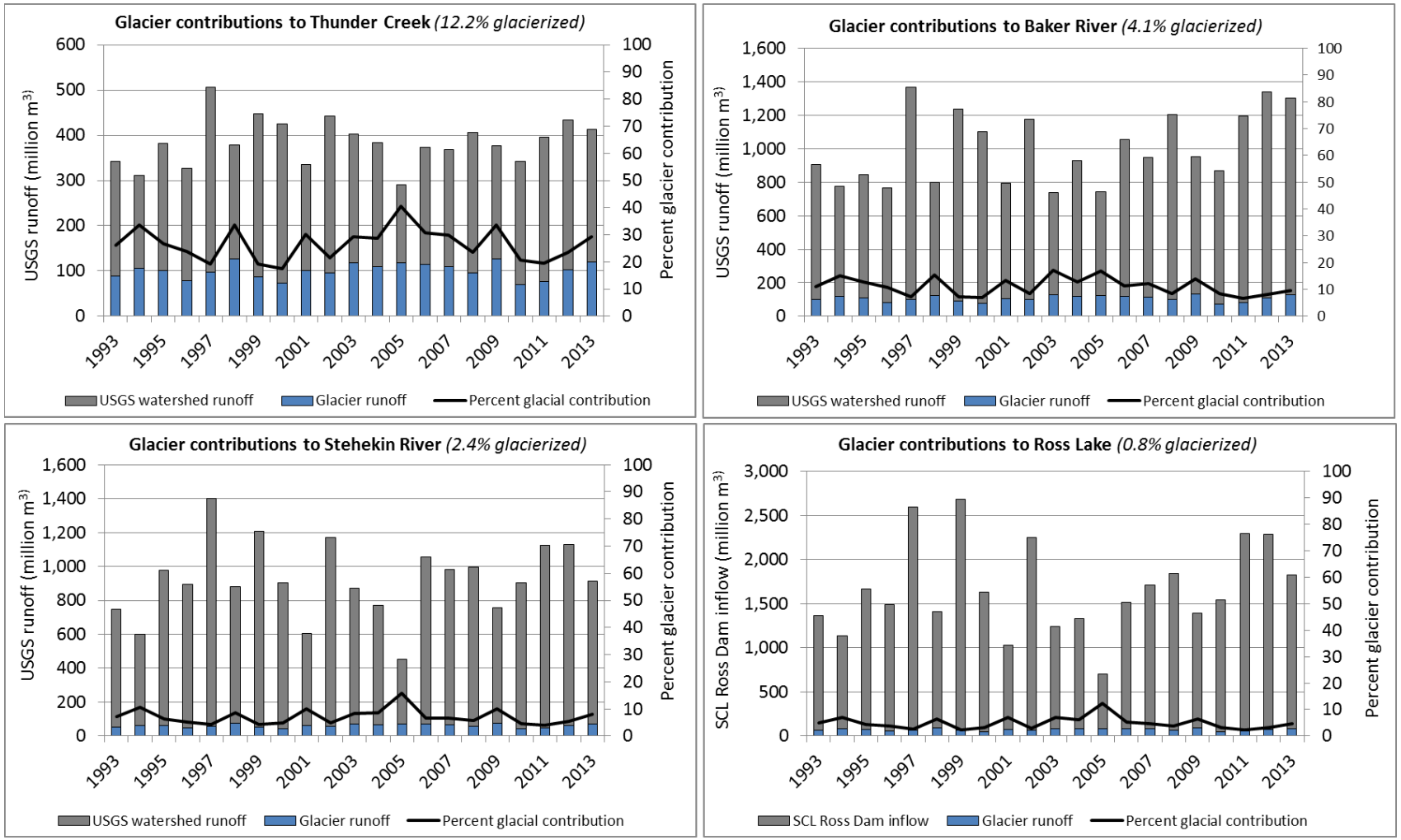

Figure 11. Provisional total May-September glacier meltwater contributions for the four watersheds containing glaciers monitored by the North Cascades National Park Complex for water years 1993-2013. Map years of glacier margin and contour data used for glacier-wide mass balances calculations: WY1993-1999 = Noisy Creek, N. Klawatti and Silver (1993 margin and contour); Sandalee (1996 margin and contour); WY2000-2012 = Noisy Creek (2009 margin, 2010 contour), N. Klawatti (2006 margin and contour), Sandalee (2004 margin, 2006 contour), Silver (2004 margin, 2004/2005 contour).

Aerial Imagery

Oblique photographs of each index glacier are shown in Figures 12-15 as records of change in area, surface elevation, equilibrium line altitude, and snow, firn and ice coverage.

Figure 12. Noisy Glacier from north, September 26, 2013.

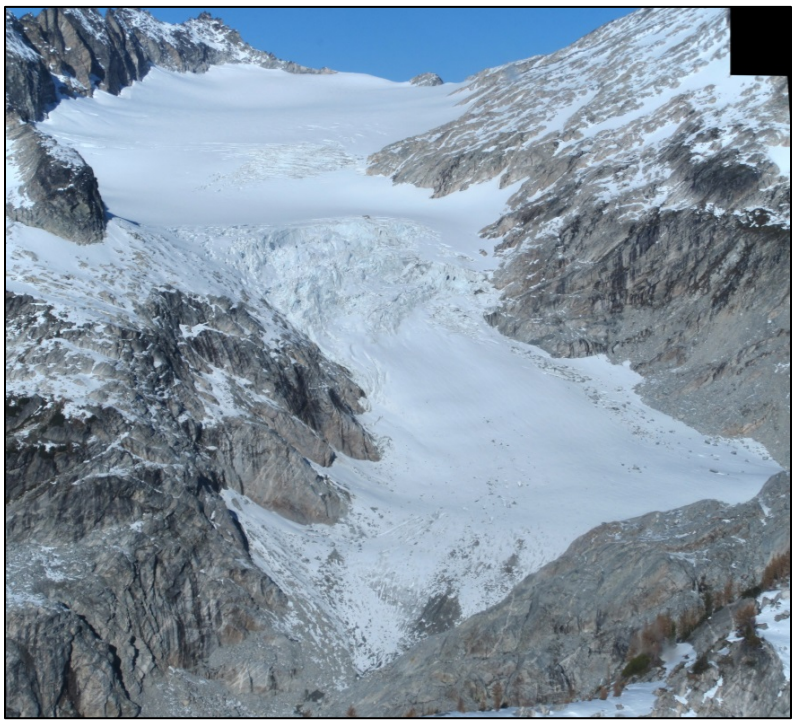

Figure 13. North Klawatti Glacier from east, October 22, 2013.

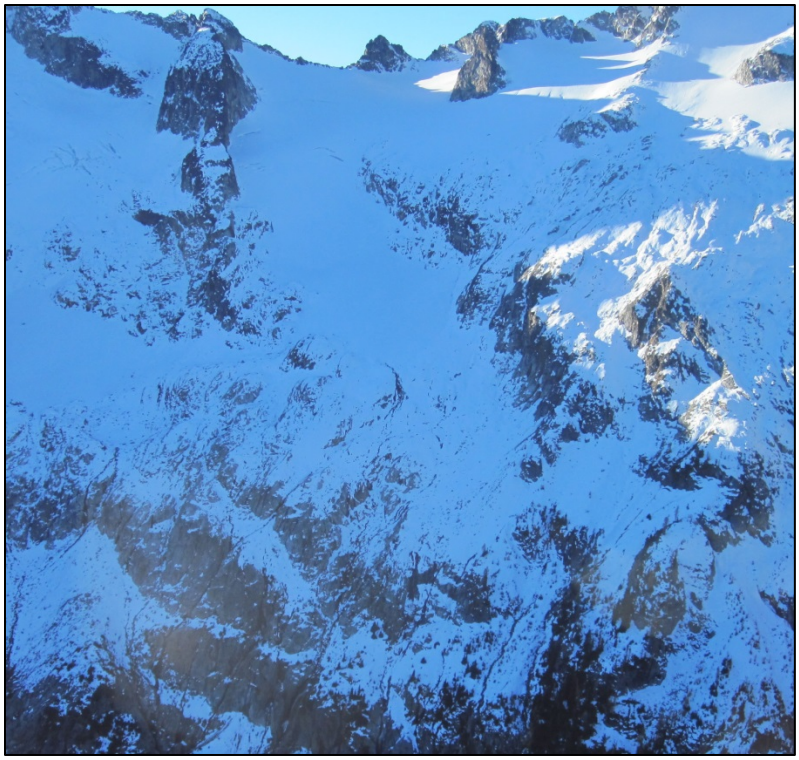

Figure 14. Sandalee Glacier from north, October 22, 2013

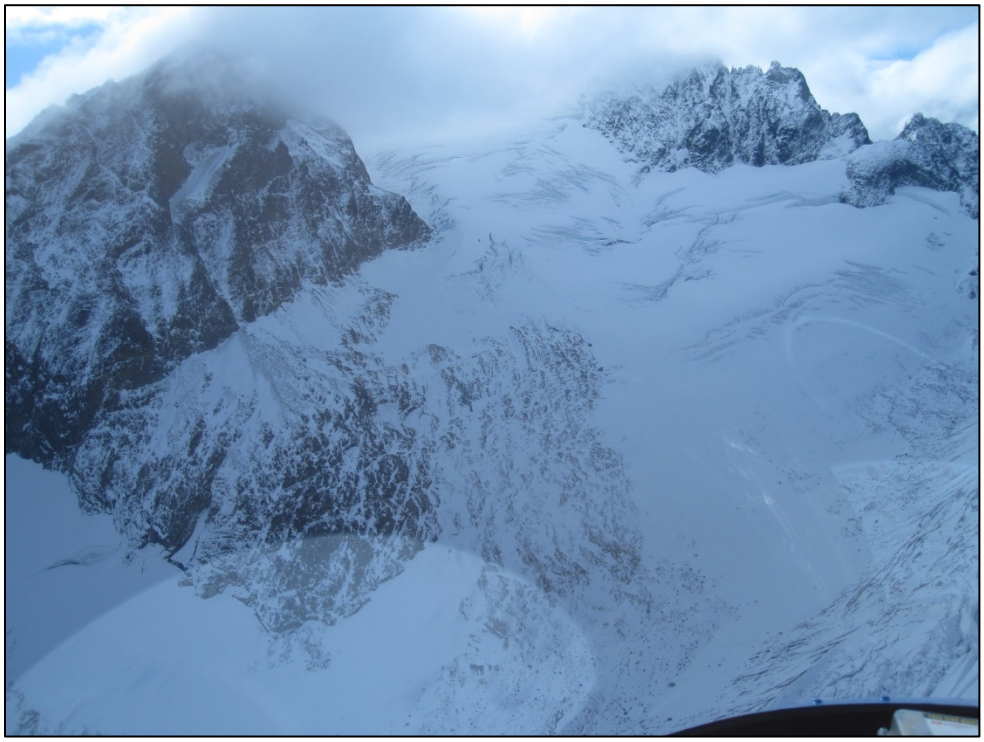

Figure 15. Silver Glacier from north, September 26, 2013.

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