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Northern Harding Icefield Glacier Mass Balance Summary

2010–2017

A mass balance stake on the Harding Icefield, October 2013.
NPS / DEB KURTZ

Northern Harding Icefield glacier mass balance summary: 2010–2017

Science Report NPS/SR—2025/240

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Abstract

Glaciers cover nearly half of Kenai Fjords National Park, serving an important role in ecosystem dynamics and attracting hundreds of thousands of visitors to the park each year. Glacial melt is important to park managers as it impacts visitor experience, infrastructure (e.g., trails and roads), and downstream habitats. Glacier mass balance is the annual gain and loss of ice calculated as a sum of seasonal measurements of accumulation and ablation (the loss of ice through melt, sublimation, and calving). Long-term glacier mass balance studies provide an established method for monitoring the status of glaciers and can be used to estimate rates of change and to predict thresholds and trigger points that could result in major changes to glacier extent and downstream systems.

This report summarizes field efforts and results of eight years of stake-based mass balance measurements on the northern Harding Icefield for water years 2010–2017. From 2010–2017, seasonal measurements were conducted at six sites on the northern Harding Icefield to quantify seasonal and annual point mass balances along an elevation gradient from 532 m to 1,290 m. Cumulative winter mass balances range from 0.47 to 1.81 meters water equivalent (m w.e.) at the lowest site of 532 meters above sea level (m a.s.l.), and 2.11 m w.e. to 3.43 m w.e. at the highest site with continuous annual data (1,230 m a.s.l). Summer mass balances range from −5.85 m w.e. to −8.35 m w.e. at the lowest site (532 m a.s.l.) and −0.54 to −2.24 at the site located at 1,230 m a.s.l. Although all sites display interannual variability in the seasonal and annual mass balance, the general trend is of decreasing mass balance. The two sites at the lowest elevations are in the ablation zone and display persistent negative mass balances. The two sites at the middle elevations have been oscillating around a zero or neutral balance and are near the Equilibrium Line Altitude (ELA). The two sites at the highest elevations have positive balances (mass gain) but have shown a decrease over the period of measurements. This has resulted in significant surface melt and elevation loss at lower elevations of Exit Glacier over the period of record.

Acknowledgments

Numerous people contributed to the success of eight consecutive years of mass balance measurements in Kenai Fjords National Park. Fritz Klasner (formerly NPS) organized the glacier monitoring strategy workshop in 2008 from which this project was conceived. Fritz and Chuck Lindsay (formerly NPS) made mass balance measurements in Kenai Fjords National Park a reality, including identifying methods, establishing the original sites, and conducting the field measurements during the early years; Chuck played a key role in every season of the first six years of the project and was invaluable in the field. In addition to Fritz and Chuck, field measurements have been supported by numerous other National Park Service and US Geological Survey scientists, while several other colleagues provided reviews that helped make this report clearer and more concise.

Introduction

Background

Kenai Fjords National Park (KEFJ) is located on the southeastern coastline of the Kenai Peninsula in southcentral Alaska (Figure 1). Nearly half the land within the park is covered by glacial ice. Most of this ice flows from the 1,800 km^2 Harding Icefield; a smaller proportion of ice coverage is contained within the numerous cirque glaciers found on many of the mountains. The park was established in 1980 by the Alaska National Interest Lands Conservation Act (ANILCA) P.L. 96-487 (2 Dec. 1980). This legislation identifies that park purposes include:

> *"to maintain unimpaired the scenic and environmental integrity of the Harding Icefield, its outflowing glaciers, and coastal fjords and islands in their natural state"* (ANILCA sec.201(5)).

In 2008, KEFJ managers held a glacier monitoring workshop to develop a strategy to research and monitor glaciers in the park (Klasner and Kurtz 2018). The strategy identified a "core" program consisting of three primary management goals: (1) Continue existing data collection efforts for weather and climate, (2) Develop a mass balance monitoring program, and (3) Continue decadal monitoring of icefield area and extent.

The following year, the park implemented a stake-based annual glacier mass balance monitoring program.

Glacier mass balance measurements are an established method of monitoring annual changes in the mass of a glacier and are described as meters of water equivalence (m w.e.) (Østrem and Brugman 1992). Winter mass balance is the total end-of-season accumulation of all frozen water gained at a site and is a measurement of the density of the snowpack at the end of the winter season (during a spring site visit). Summer mass balance is a final sum of any accumulation and loss of frozen water that occurs over the summer ablation season.

This report documents eight years (water years 2010–2017) of glacier mass balance measurements at KEFJ. It begins with an introduction to the study area, providing context to distinguish the climate on the northern Harding Icefield from other regions of Alaska where glacier mass balance is monitored. The methods and results of the measurements are then summarized. This is followed by a discussion of the results and recommendations for future measurements.

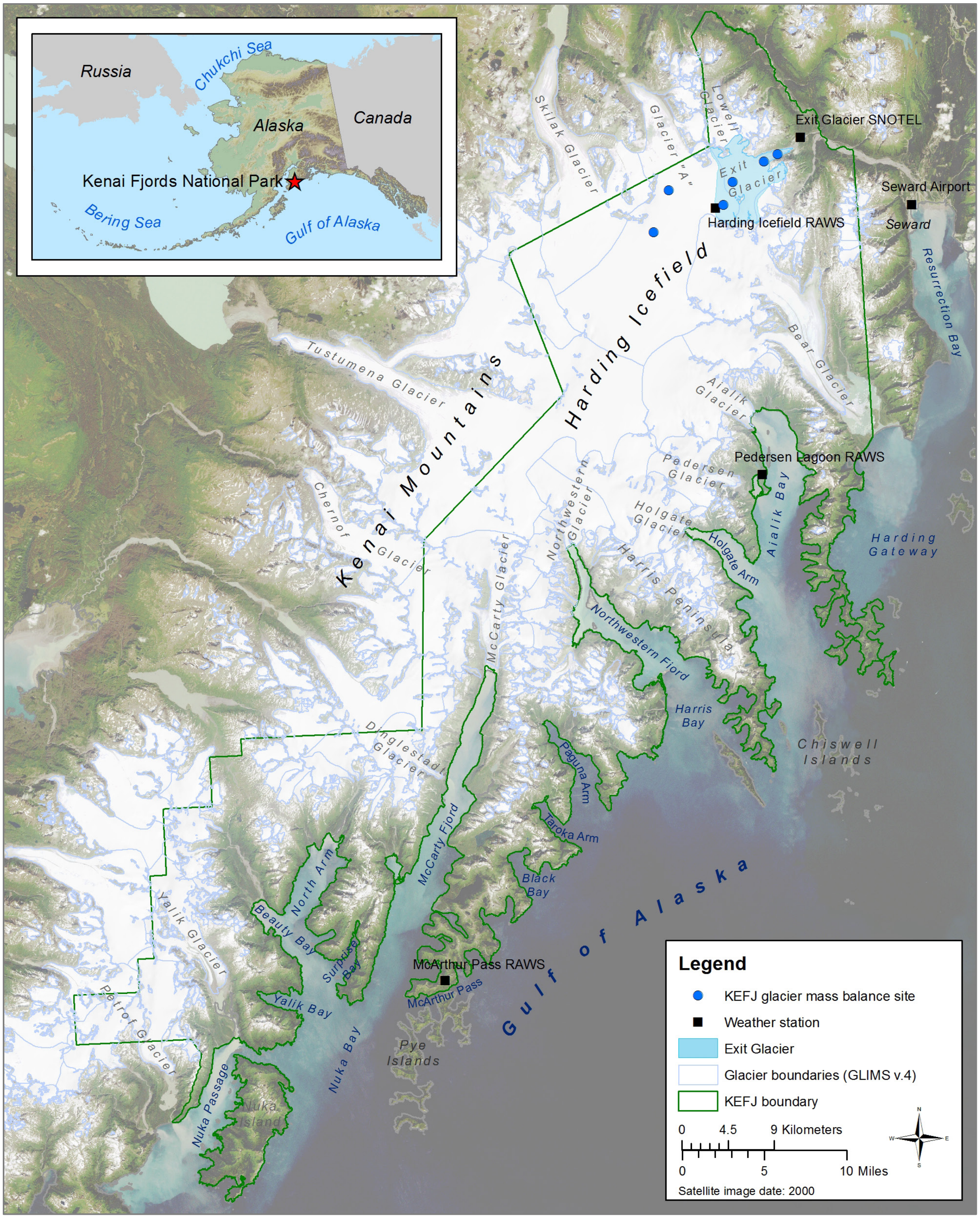

Figure 1. Map of Kenai Fjords National Park glacier mass balance sites and automated weather stations. The inset map provides a geographic reference for other features mentioned in this report.
NPS / DEB KURTZ

Study Area

The Harding Icefield is located on the Kenai Peninsula in southcentral Alaska between latitudes 59° 25' and 60°16' N and longitudes 149° 32' and 150° 59' W at the northern end of the Gulf of Alaska (Figure 1). Spanning an area of 1,800 km^2, the icefield rises from sea level at the termini of tidewater glaciers on its eastern periphery to 1,400 m above sea level (a.s.l.) on the central plateau (Truffer 2014).

The Harding Icefield is differentiated from other glaciated regions in Alaska by its geography and climate. Situated on the northwest corner of the Gulf of Alaska, the local climate is largely influenced by proximity to the ocean, high latitude, and a complex landscape ranging from convoluted shorelines along the fjords to nearly 2,000 m high peaks protruding as nunataks from the icefield. The southeast-facing portion of the icefield is characterized by relatively moderate temperatures and abundant precipitation as moist air masses moving inland from the Gulf are forced upward by the Kenai Mountains, causing moisture to fall as heavy precipitation on the east-southeastern (windward) side and leaving the west-northwestern (lee) side of the icefield drier. In contrast, glaciers in the Alaska Range have greater elevation gradients and are located within a continental climate (i.e., less precipitation and more extreme temperatures). Glaciers in southeast Alaska, including those within Glacier Bay National Park and Preserve and the nearby Coast Mountains, also exhibit maritime-continental gradients. However, due to the topographic influence of the islands in the Alexander Archipelago, these glaciers are not as directly exposed to maritime influences and incoming storms as the Harding Icefield is. In addition, many of the glaciers in southeast Alaska form at higher elevations than the Harding Icefield.

Since the 1950s, the Harding Icefield has been thinning and shrinking (Adalgeirsdottir et al. 1998; Giffen et al. 2014; Loso et al. 2014). The most recent measurements indicate that the areal extent of glacial ice within and adjacent to KEFJ has decreased by 11% from the 1950s to the late 2000s (Loso et al. 2014; Black and Kurtz 2022). From 2000–2019, the mean elevation change rate of Alaska's glaciers was -0.91 ± 0.08 m yr^{-1} (Hugonnet et al. 2021).

KEFJ's glacier mass balance monitoring is focused on Exit Glacier, an east-northeast flowing, land-terminating outlet glacier in the northern part of the Harding Icefield (60° 10'N, 149° 43'W). As the only glacier in the park that can be accessed via a road, Exit is the most accessible land-terminating glacier in the park and, therefore, a primary visitor destination. Unlike the park's tidewater glaciers, Exit Glacier is roughly 16 km from the ocean (Resurrection Bay), lessening the maritime influence that moderates temperature and intensifies precipitation in the fjords. Exit Glacier covers an area of 37.8 km^2 and ranges from 123 to 1,666.7 m a.s.l. (Figure 2). From the time it reached its maximum Little Ice Age extent in the early 1800s until 2016, Exit retreated 2.5 km (Kurtz and Baker 2016). From 2016 to 2023, Exit Glacier retreated an additional 334 m.

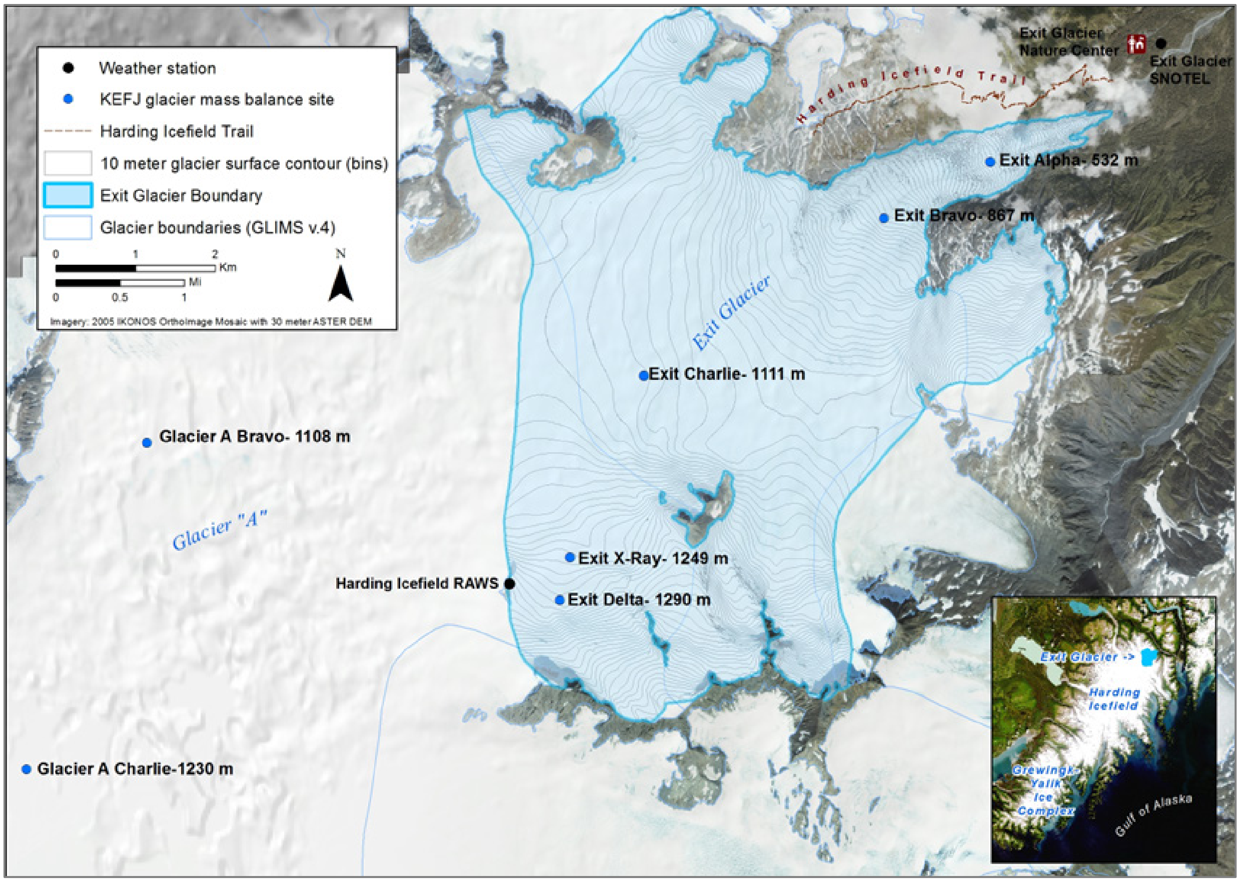

Figure 2. Map of glacier boundaries, 10 m elevation contours on Exit Glacier, mass balance sites, and weather stations on the northern Harding Icefield. The glacier to the west of Exit Glacier is unnamed and is referred to here as “Glacier A” for ease of communication. NPS / DEB KURTZ

Methods

KEFJ's mass balance measurements are based on the glaciological method, which uses point measurements collected seasonally as in-situ observations at snow pits and stakes to calculate winter, summer, and annual net balances.

Site Selection

Sites were located based on accessibility, lack of crevasses above/at/below the site where the stakes could flow with the ice without getting lost in a crevasse, and proximity to laser altimetry lines from previous research conducted by Arendt et al. (2002). The sites were placed along a longitudinal profile to measure the altitudinal distribution of accumulation and ablation and were located to provide an unbiased representation of their respective elevations (Figure 2). For example, although avalanche debris and wind-deposited snow contribute to a glacier's annual accumulation, the mass balance of these locations may not be representative of the mass balance for that elevation glacier-wide.

Stakes, consisting of 3-m steel sections coupled together for easy lengthening and shortening, were installed at four sites on Exit Glacier in 2009 (one in the accumulation zone, one at the estimated equilibrium line of altitude (ELA) and two in the ablation zone.) In 2010, two sites were added in the accumulation zones and estimated ELA of both Aialik Glacier and an unnamed, north-flowing glacier due west of Exit between Lowell and Skilak Glacier (for ease of communication, this glacier will be referred to as Glacier A in this document) (Table 1). The ELAs were estimated based on available imagery and personal observations by NPS staff prior to 2009. Sites were not identified in the ablation zones of these two glaciers due to inaccessibility related to crevasses. Stake installation dates were staggered so that methods and logistics could be implemented and tested on Exit Glacier before implementing on other glaciers. During the fall 2011 ablation measurement at the Aialik sites, the stakes were located under more than two meters of new snow that had fallen in August. It was apparent that the amount of snow received in this area would require numerous site visits to extend the stakes and maintain their accessibility. KEFJ did not have the resources for multiple helicopter procurements, so the sites on Aialik Glacier were discontinued, and all efforts were focused on Exit Glacier and Glacier A.

Table 1. Site coordinates, elevations, and specific location descriptions.

Site	Northing	Easting	Elevation (m)	Notes on Site Location
Exit Alpha	60.17579	−149.667	532	Exit Alpha is in the ablation zone at a site that is easily accessed by foot.
Exit Bravo—side	60.16933	−149.6977	867	Exit Bravo was installed at the location of a lower-elevation snow pit site from previous monitoring efforts conducted by the park. This site would allow the snow pit data to be referenced at approximately the same elevation but off-centerline.
Exit Bravo—center	60.16898	−149.6984	800.1	In 2015, the slope at Exit Bravo became too steep to access by helicopter, so a new Exit Bravo site was relocated slightly down-glacier and closer to the center of the glacier in a flatter area.
Exit Charlie	60.15433	−149.74825	1111	Exit Charlie is located near the 2009 estimated ELA.
Exit Delta	60.13079	−149.77078	1290	Exit Delta is at approximately the same elevation as the Harding Icefield Remote Automated Weather Station (RAWS). This site is located near the high-elevation snow pit site from the park's previous monitoring efforts but closer to the glacier centerline to avoid snowdrifts and local effects from nearby nunataks. (Although drifting is a process of accumulation, we were aiming to find sites that are most representative of that elevation across the entire glacier).
Exit X-ray	60.13449	−149.76786	1249	Exit X-ray was installed in WY 2015 to replace Exit Delta because Exit Delta was frequently unlocatable (perhaps due to high winds breaking the stake or full burial possibly due to deep snow drifts.)
Glacier A Bravo	60.15101	−149.86185	1108	Glacier A Bravo is located at the 2009 estimated ELA of Glacier A.
Glacier A Charlie	60.11463	−149.89375	1230	Glacier A Charlie is in the accumulation zone of Glacier A.

Seasonal Measurements

We adapt methods from the US Geological Survey and North Cascades National Park to implement the glaciological method, an established, stake-based manual surface measurement for an accurate, relatively efficient field-based method to monitor annual changes in surface mass balance (Østrem, G. and Brugman M. 1992; Trabant and March 1999; Mayo L. et al. 2004; Reidel et al. 2008; Cogley et al. 2011).

Multi-year mass balance stakes serve as markers against which changes in glacier surface height are compared. These marker locations, measured by a mapping grade (10 cm accuracy) Trimble GPS with an external antenna, are also used to document seasonal glacier velocities.

Mass balance measurements consist of three site visits throughout the water year (WY; Figure 3). Summer mass balance measurements (conducted in the fall) establish a base minimum measurement for the upcoming WY and provide a final summer balance for the previous WY's annual balance calculation. A mid-winter visit may be necessary in late-January/ February to extend the stakes to prevent burial by winter accumulation and to increase efficiency when relocating them at the spring visit. A spring visit provides winter balance measurements.

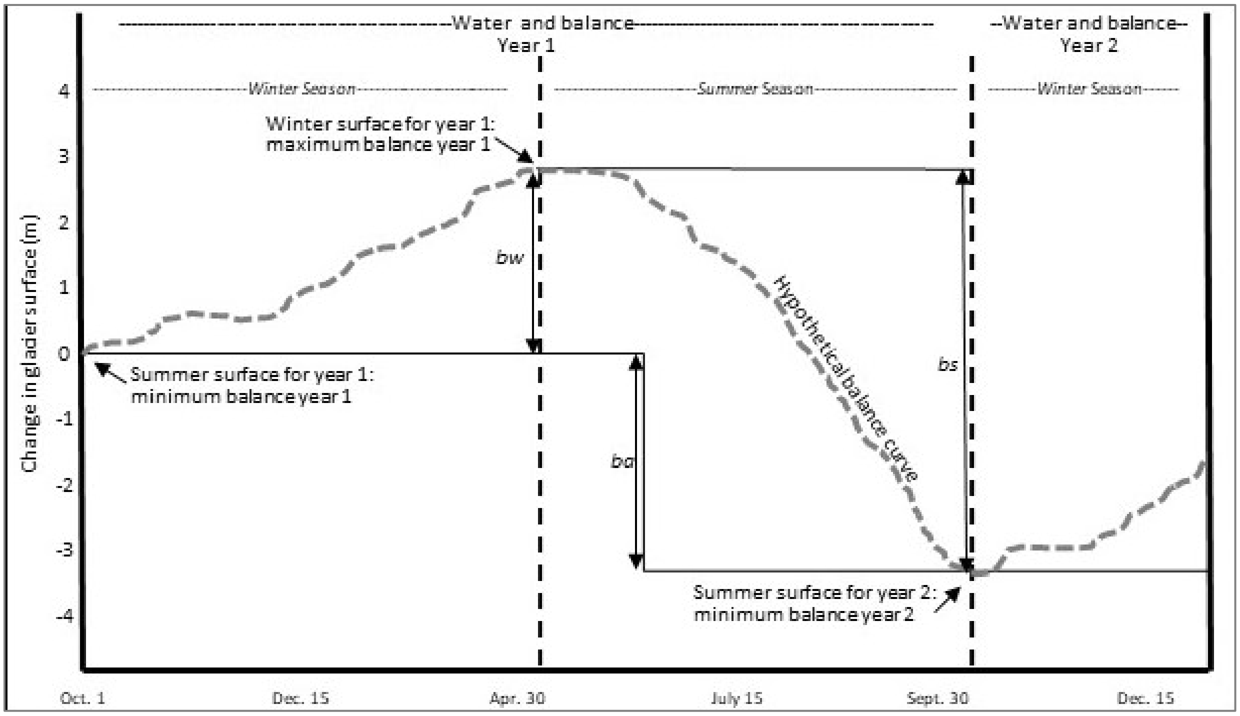

Figure 3. Glacier surface change and mass balance measurements throughout a water year: winter balance (bw), summer balance (bs), and annual balance (ba). NPS

Field surveys are conducted on a floating-date system with some hybridization of the stratigraphic system (Cogley et al 2011), where the annual minima surface in the fall (end of ablation period) and annual maxima surface in the spring (end of accumulation period) are targeted for measurements. Despite the interest and efforts to hit these conditions, the actual dates are determined by suitable weather for flying to the sites.

Fall Site Visit

The fall site visit is a measurement of summer mass balance (the minimum surface elevation for the WY) and is scheduled for September. If we find early-season snow accumulated on the icefield during the fall measurements, we remove it to expose the summer surface for the minimum annual mass measurement and return it to the site post-measurement to be included in the next year's measurement. During a fall visit, a piece of $1m^2$ plywood with a hole in the center is placed on the surface of the glacier centered around the stake to mark the end minimum surface from which the next WY balance will be calculated. This plywood increases certainty when probing seasonal accumulation in the spring and when identifying remaining winter accumulation during the following fall measurement, as it clearly delineates the end/beginning WY surface at accumulation sites where old snow and previous firn can be difficult to distinguish in maritime environments.

The lower elevation sites are accessed on foot and are typically measured the third week of September. A mapping grade GPS is used to measure the geographic coordinate and surface elevation of each stake and allows us to calculate flow velocities and direction. When the site was established, an index site, a fixed coordinate on the icefield that we return to regardless of the glacier motion, was identified. This site is also mapped with the GPS at the fall site visit to provide a measurement of surface elevation change at a stationary point.

Spring Site Visit

Winter on the Harding Icefield occurs from approximately October–April. Winter balance measurements are scheduled for the last week in April/first week in May to target maximum seasonal snowpack for measurement of total accumulated water content for the winter. Ideal timing for this measurement occurs when the air temperature is near freezing, precipitation is no longer frozen, and the surface has not begun to melt. Although average daily maximum temperatures on the icefield may exceed freezing and the lowest site is typically close to isothermal during the site visit, late spring and summer storms may result in additional accumulation at the higher stakes after the measurements have occurred.

Winter Accumulation

Winter seasonal snow accumulation is quantified by measuring snow depth and density.

Depth

At each measurement site, snow depth is measured via a combination of probing, making snow height readings on stakes, and/or coring the full winter snowpack. Exact measurement details depend upon conditions found in the field and equipment available. Snow depths on the northern Harding Icefield can exceed 7 meters, presenting a challenging and time-consuming effort to measure the entire depth.

During the early years of WY 2010–2016, spring snow depth was determined using probe depths and/or a measurement of surface elevation in relation to the stake height (the height of stake sticking out of the glacier surface in the spring relative to the height of stake in the fall). Probing is a simple method of measuring snow depth directly and consists of pushing a snow probe (a metal rod marked with lengths) vertically through the entire seasonal snow column. There are two major challenges to probing on the northern Harding Icefield: (1) There may be ice lenses present. These can be mistaken for glacial ice or they can be too thick to penetrate, making probing futile. (2) If the stake and/or the location of the plywood to target is not located, it can be extremely difficult to differentiate between firn and new snow. If the stake is visible at the spring visit, the site is probed next to the stake to target the plywood. If there is uncertainty that the plywood is being reached, a steam drill can be used to confirm that the bottom layer is plywood and not an ice lens. The change in stake height from the fall to spring site visit is also used to determine and/or validate snow depth. If the stake is leaning, the actual stake height is calculated later in the office using trigonometry. If the stake is not found during the spring visit, a second stake is installed at the site and is used to cross-reference stake heights with the existing stake during the fall visit. If the plywood and/ or stake were not located during the spring visit, snow depth is calculated based on an average of multiple probes.

Density

During WY 2010–2016, density was measured by digging a two-meter pit and measuring the weight of the top two meters using cores collected with a Norwegian tube (a 7.5 cm × 40 cm pipe). The third meter of snow from the surface was measured using a Kovacs corer, as illustrated in Figure 4. If the snow depth was around four meters and there was time, a deeper pit was dug to core and weigh the entire snowpack. If snow depth was greater than four meters, the lower snow density was estimated based on the top snow densities.

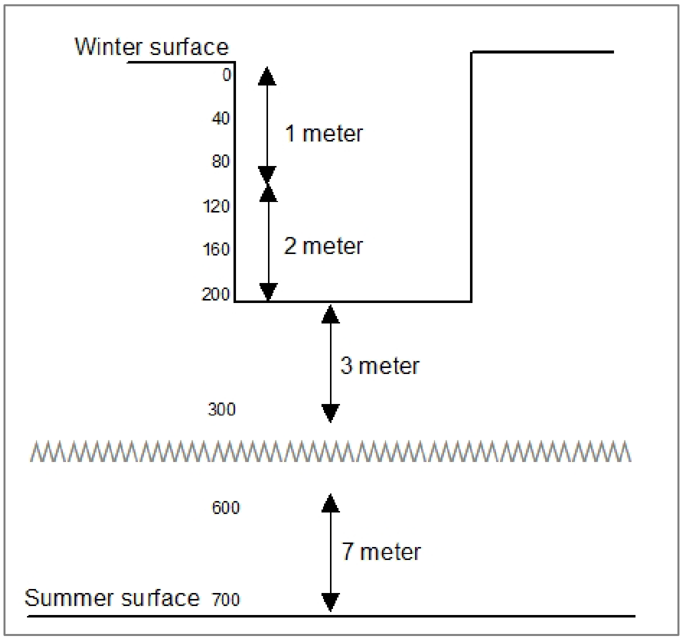

Figure 4. Diagram of a snow pit. Density is measured from a two-meter snow pit. The top 2 m are measured in 40 cm increments along a shaded wall of the pit. The third meter of snow is measured as a core taken from the bottom of the snow pit floor. NPS / DEB KURTZ

WY 2017

In WY 2017, NPS acquired additional equipment to core the entire winter accumulation depth, greatly increasing confidence and decreasing errors in snow depth and density measurements. A two-meter snow pit is still dug and sampled with the Norwegian corer, but deeper snow is sampled with a Kovacs corer attached to an angle drill for measurements of the entire winter accumulation (Figure 5).

Figure 5. Lowering the Kovacs corer into the hole to sample below the two-meter-deep floor of the snow pit. NPS / D. KURTZ

Geodetic Measurements

On each visit, the location and surface elevation of the stake and the surface elevation of the static index site are recorded with a mapping grade Trimble GPS and a Zephyr-2 external antenna with horizontal accuracies ranging from 5–100 cm (typically, more than 50% of the points have an accuracy of less than 50 cm). A manual record of stake height, snow depth, and snow density are recorded on data sheets. GPS data is post-processed in Pathfinder Office and exported to a shapefile projected to UTM 6N, WGS 1984. Coordinate and altitude data (recorded as height above ellipsoid), available in an attribute table in ArcGIS, are used to calculate stake displacement, glacier flow velocities, and change in surface elevation.

Point Mass Balance

Snow depths and densities are used to calculate winter balance (b_w), summer balance (b_s), and annual balance (b_a).

$$ba = bw + bs$$

Bulk density is calculated for measurements taken in each combination snow pit and core, providing the bulk density of the full annual snow column. For WY 2010–2016, the full snowpack depth was often not sampled due to equipment and/or time limitations. In cases where this was true, the depth of snow measured below the lowest sample was assumed to be the same as that of the deepest measured sample (usually a core). This is further discussed in the results.

Spring and fall site visits are scheduled to target glacier-wide maximum and minimum mass during a water year. At individual sites, the timing of mass maxima and minima vary as lower elevation sites experience a longer melt season, while upper elevation sites may be accumulating snow. Actual field dates are determined by weather and helicopter availability, in addition to observed ground conditions and forecast (see Results section).

Weather Monitoring

Five weather stations are located on the eastern margin of the Harding Icefield. The Southwest Alaska Network of the NPS Inventory and Monitoring program (SWAN) maintains three remote automated weather stations (RAWS) at varying altitudes within KEFJ (see Figure 1). McArthur Pass RAWS is the most southern station and is located on the outer coast at 300 m a.s.l. Pedersen Lagoon RAWS is situated centrally along the north-south axis of the icefield, is coastal yet not directly exposed to the open Gulf of Alaska (it is 35 km up-fjord in Aialik Bay), and is the site located at the lowest altitude at 150 m a.s.l. The Harding Icefield RAWS is the most northern, most inland, and highest-altitude site, situated at 1,280 m a.s.l.

Three weather stations are located within 15 km of Exit Glacier; of these, two are located within the Exit Creek drainage divide (Figure 6). The Harding Icefield RAWS, located on a nunatak on the icefield west of Exit Delta, has been operating since 2005. The Natural Resource Conservation Service, with the support of the NPS, installed and maintains a SNOTEL station at elevation 122 m near the terminus of Exit Glacier since 2011. The Seward airport station (508371-26438) is located at an elevation of 7 m and approximately 13 km from Exit Glacier’s terminus. This station has the longest period of observation in the Seward area, with continuous records beginning in 1998 and intermittent data collection since 1908 (although this station has been relocated within Seward several times prior to 1998).

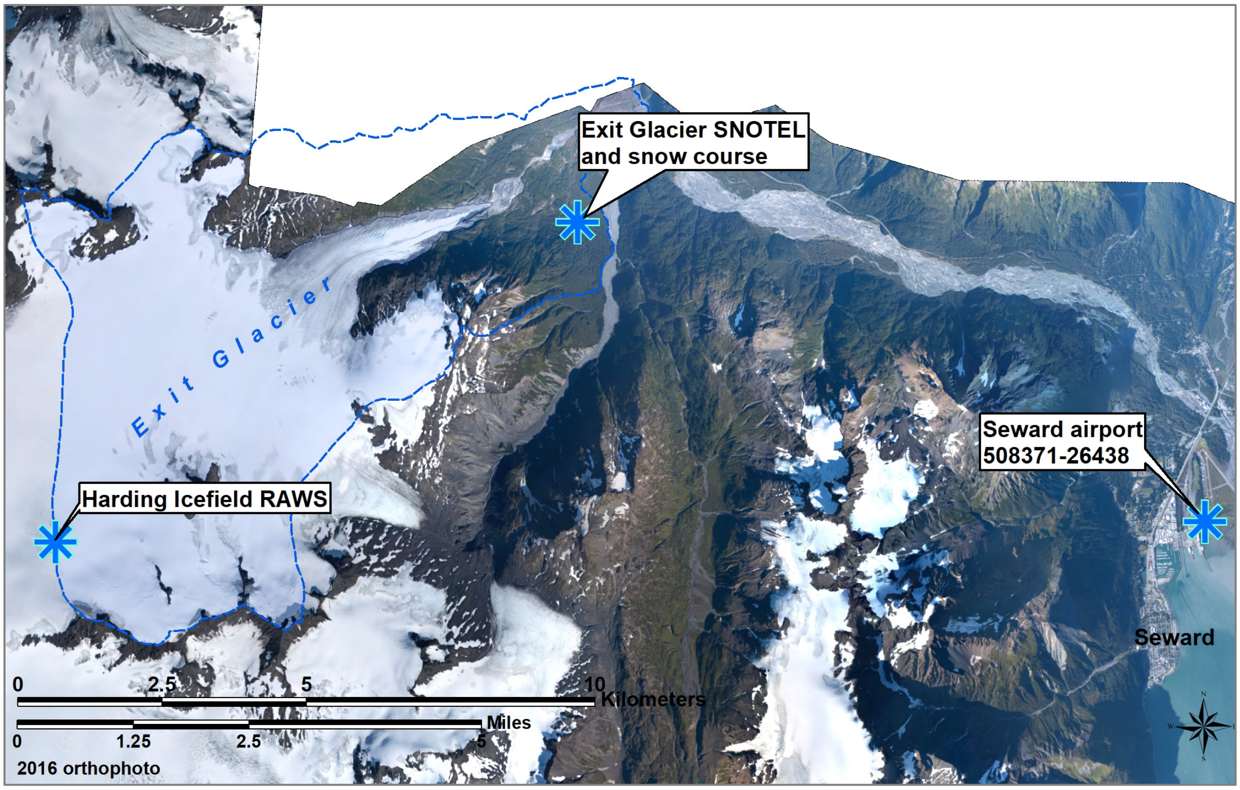

Figure 6. Three weather stations are located within 15 km of Exit Glacier. NPS / DEB KURTZ

Results

Seasonal Measurements

From 2010 to 2017, we visited the mass balance sites for seasonal measurements each spring and fall. All spring measurements occurred within a three-week period between April 17–May 3 (Table 2). Fall measurements were conducted during a six-week timeframe, determined by good weather windows (or, in the case of 2013, a three-week government shutdown) and occurred as early as September 4 and as late as October 26. We have not attempted to model any additional accumulation that may occur after the spring measurements have been completed or melt that may occur after the fall measurements, and we recognize that this is a potential source of error resulting in an underestimate of the seasonal balances.

Mid-winter site visits were conducted every year except 2010 (lack of recognition of need), 2012 (inaccessibility due to ground fog), and 2013 (inadequate funding).

Table 2. Site visit dates.

	WY 2010			**WY 2011**			**WY 2012**			**WY 2013**			**WY 2014**			**WY 2015**			**WY 2016**			**WY 2017**		
Site Name	**Start**	**Mid (End of Winter)**	**Finish**	**Start**	**Mid (End of Winter)**	**Finish**	**Start**	**Mid (End of Winter)**	**Finish**	**Start**	**Mid (End of Winter)**	**Finish**	**Start**	**Mid (End of Winter)**	**Finish**	**Start**	**Mid (End of Winter)**	**Finish**	**Start**	**Mid (End of Winter)**	**Finish**	**Start**	**Mid (End of Winter)**	**Finish**
Exit Alpha	8/28/09	4/27/10	9/21/10	9/21/10	5/3/11	9/22/11	9/22/11	4/27/12	10/12/12	10/12/12	4/21/13	10/23/13	10/23/13	4/24/14	9/24/14	9/24/14	5/2/15	10/1/15	10/1/15	5/14/16	9/19/16	9/19/16	4/17/17	10/3/17
Exit Bravo	9/4/09	4/26/10	9/10/10	9/10/10	5/3/11	9/26/11	9/26/11	4/27/12	10/9/12	10/9/12	4/21/13	10/26/13	10/26/13	4/24/14	9/23/14	9/23/14	5/2/15	9/19/15	9/19/15	5/13/16	9/10/16	9/10/16	4/17/17	10/3/17
Exit Charlie	9/4/09	4/26/10	9/10/10	9/10/10	5/2/11	9/26/11	9/26/11	4/26/12	10/9/12	10/9/12	4/20/13	10/26/13	10/26/13	4/23/14	9/23/14	9/23/14	5/1/15	9/19/15	9/19/15	5/13/16	9/10/16	9/10/16	4/17/17	9/19/17
Exit Delta/ X-Ray	9/4/09	4/25/10	9/10/10	9/10/10	5/2/11	9/26/11	9/26/11	4/26/12	10/9/12	10/9/12	4/20/13	10/26/13	10/26/13	4/23/14	9/23/14	9/23/14	5/1/15	9/24/15	9/24/15	5/13/16	9/10/16	9/10/16	4/17/17	9/19/17
Glacier A Bravo	N/A	N/A	9/11/10	9/11/10	5/2/11	9/26/11	9/26/11	4/25/12	10/9/12	10/9/12	4/19/13	10/26/13	10/26/13	4/22/14	9/23/14	9/23/14	5/1/15	9/19/15	9/19/15	5/14/16	9/10/16	9/10/16	4/18/17	9/19/17
Glacier A Charlie	N/A	N/A	9/11/10	9/11/11	5/1/11	9/26/11	9/26/11	4/25/12	10/9/12	10/9/12	4/19/13	10/26/13	10/26/13	4/22/14	9/23/14	9/23/14	5/1/15	9/24/15	9/24/15	5/15/16	9/10/16	9/10/16	4/18/17	9/19/17

Winter Accumulation

From 2010–2017, snow depth (winter accumulation) on Exit Glacier varied between sites and at each site interannually (Figure 7). The minimum snow depth recorded was 1.0 m measured at Exit Alpha in 2014. Maximum snow depth was 8.5 m measured at Exit Delta in 2010. The average snow depths for these two sites were 2.6 m and 7.3 m, respectively.

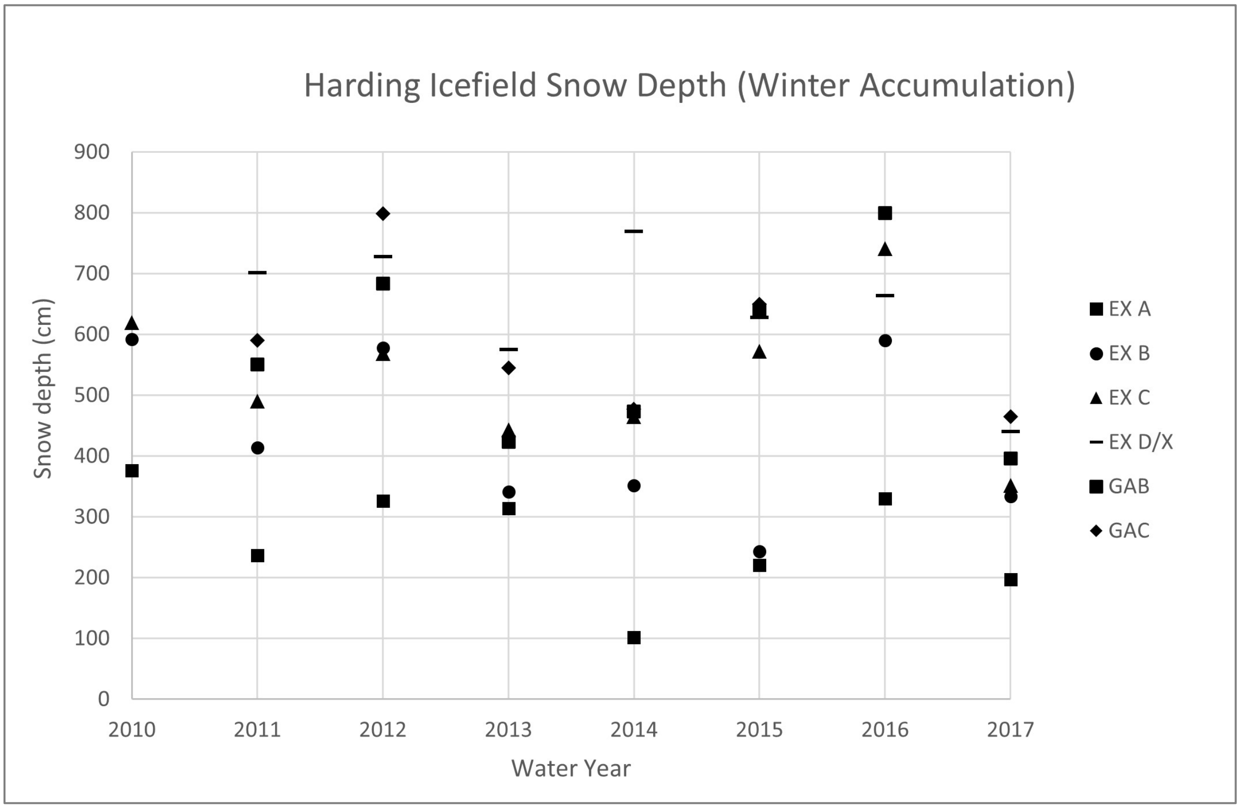

Figure 7. Snow depth at each site on date of spring field visit, by water year. NPS / DEB KURTZ

Below-Pit Snow Density Error Estimate

Prior to the initiation of the mass balance project, KEFJ staff monitored Harding Icefield winter balance by digging two snow pits on Exit Glacier, one at a site located at 820 m a.s.l. (at the original Exit Bravo) and one near the Harding Icefield RAWS at 1,314 m a.s.l. (near Exit Delta) (Klasner 2008; Tetreau 2006). From 2000 to 2010, there were years when full-depth snow pits were dug at Exit Bravo and one year when a full-depth pit was dug at Exit Delta; other years only partial snow pits were dug due to time constraints. Using data from the years where full-depth bulk density is known, we tested the representativeness of the mean snow core sampled between 2–3 m from the surface on the density of the remaining annual snowpack (>3 m from the surface). Results indicate that the bulk density of the lowest part of the snowpack (>3 m from the surface) is 103% that of the mean core sampled between 2–3 m below the surface for the five pits analyzed. This indicates that using the density of the core sampled between 2–3 m from the surface to estimate bulk density for the remaining snowpack underestimates the bulk density (Figure 8). The full pit that was dug at the upper site was dug during a low snow year (4.55 m). At this site, the bulk density of the 2–3 m core was 97% of the average density measured from 3 m to the bottom of the snow pit. Therefore, the method we used to calculate bulk density for WY 2010–2016 based on the Kovacs corer sampled 2–3 m below the surface to calculate the remaining snowpack's bulk density resulted in a minimum 3% underestimation.

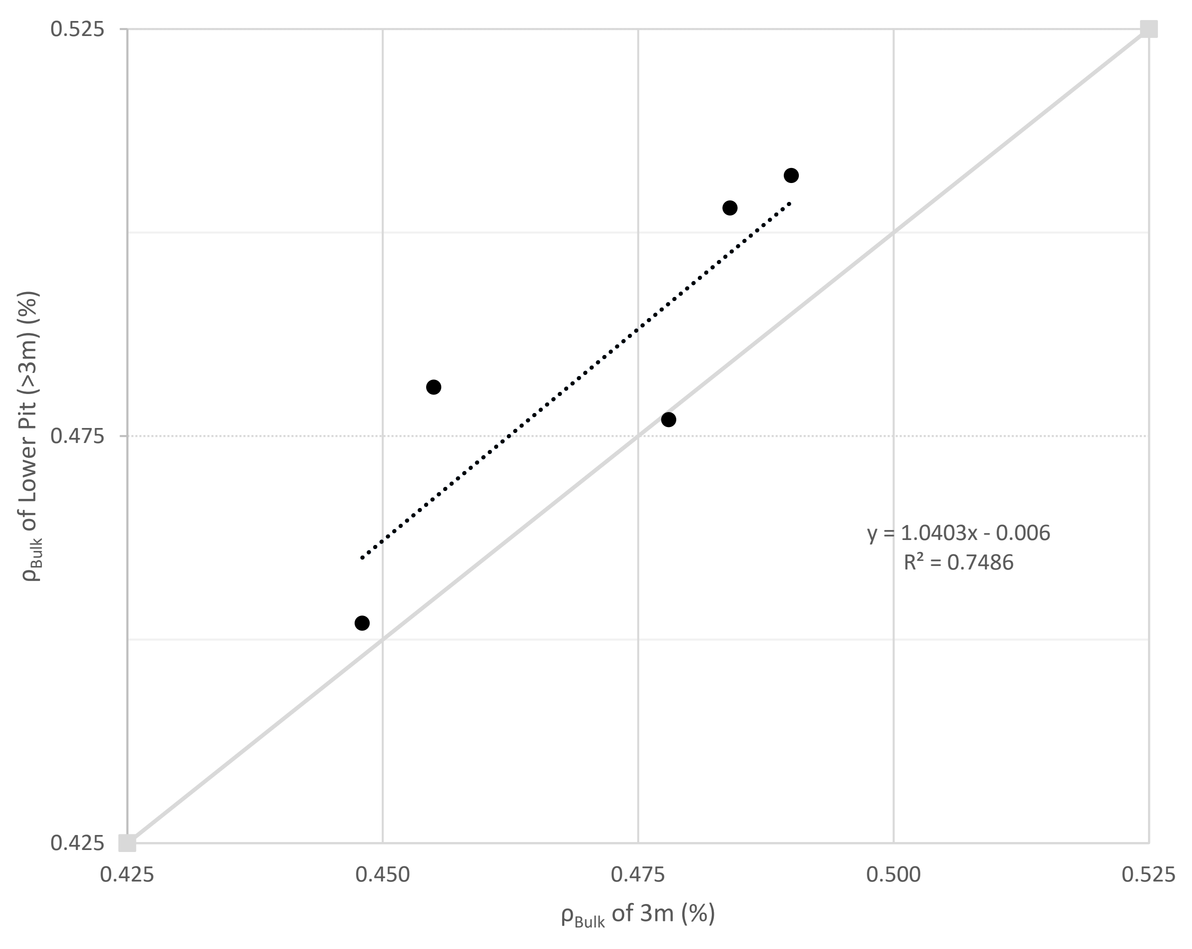

Figure 8. Relationship between bulk density of the 2–3 m sample vs. the snowpack below 3 m. The gray line provides a 1:1 reference line. NPS

Point Mass Balance

Annual point-based mass balance data tabulated by site are presented in Table 3 and summarized below. Detailed accounts of each season’s data collection efforts are presented in Appendix B.

Table 3. Mass balance, velocity, snow depth, and bulk snow density for each site.

Site	WY	Mass Balance (m w.e.)			Velocity (m/day)			Winter Snow Depth (cm)	Winter Bulk Density (g/cm^3)
		Winter	Summer	Annual	Winter	Summer	Water Year		
Exit Alpha	2010	1.78	N/A	N/A	0.27	0.28	0.27	376.00	0.47
	2011	1.02	−6.30	−5.28	0.27	0.32	0.29	237.00	0.43
	2012	1.79	−5.85	−4.06	0.27	0.32	0.29	326.00	0.55
	2013	1.35	−7.33	−5.99	0.26	0.29	0.28	314.00	0.43
	2014	0.47	−7.38	−6.91	0.23	0.28	0.25	102.00	0.46
	2015	0.88	−8.35	−7.47	0.20	0.28	0.24	221.00	0.4
	2016	1.81	−8.15	−6.33	0.20	0.24	0.21	330.00	0.55
	2017	0.76	−7.25	−6.49	0.18	0.22	0.20	197.00	0.42
	Mean	**1.24**	**−7.23**	**−6.08**	**0.24**	**0.28**	**0.25**	**262.88**	**0.46**
Exit Bravo	2010	2.51	−3.74	−1.23	N/A	N/A	0.26	592.00	0.42
	2011	1.86	−3.98	−2.12	0.24	0.27	0.25	414.00	0.45
	2012	2.66	−2.77	−0.11	N/A	0.30	0.28	578.00	0.46
	2013	1.40	−4.68	−3.28	0.24	0.30	0.27	341.00	0.41
	2014	1.65	−4.08	−2.42	0.23	N/A	0.30	353.00	0.47
	2015	2.60	−5.46	−2.86	0.22	0.28	0.24	448.00	0.58
	2016	3.84	−5.15	−1.31	N/A	0.30	N/A	590.00	0.65
	2017	1.31	−5.09	−3.78	0.22	0.25	0.23	334.00	0.35
	Mean	**2.23**	**−4.37**	**−2.14**	**0.23**	**0.29**	**0.27**	**456.25**	**0.47**
Exit Charlie	2010	2.96	−2.43	0.53	N/A	N/A	0.06	620.00	0.48
	2011	2.20	−2.15	0.05	0.06	0.08	0.06	490.00	0.45
	2012	2.55	−1.69	0.86	0.06	0.07	0.06	569.00	0.66
	2013	1.87	−3.09	−1.22	0.04	0.06	0.05	443.00	0.42
	2014	2.24	−4.36	−2.12	0.04	0.07	0.06	465.00	0.48
	2015	2.54	−2.54	0.00	N/A	0.07	0.05	572.00	0.44
	2016	4.25	−3.49	0.76	0.04	0.06	0.05	741.00	0.57
	2017	1.49	−2.70	−1.21	0.04	0.06	0.05	351.50	0.36
	Mean	**2.50**	**−2.81**	**−0.29**	**0.05**	**0.07**	**0.06**	**531.44**	**0.48**

Table 3 (continued). Mass balance, velocity, snow depth, and bulk snow density for each site.

Site	WY	Mass Balance (m w.e.)			Velocity (m/day)			Winter Snow Depth (cm)	Winter Bulk Density (g/cm^3)
		Winter	Summer	Annual	Winter	Summer	Water Year		
Exit Delta	2010	N/A	N/A	N/A	N/A	N/A	N/A	849.00	0.45
	2011	3.11	−1.40	1.71	0.09	0.07	0.08	702.00	0.44
	2012	3.62	−0.71	2.90	N/A	0.09	0.08	728.00	0.47
	2013	2.10	−1.66	−0.43	0.09	0.06	0.08	575.00	0.37
	2014	3.85	−2.65	1.19	0.08	0.09	0.08	770.00	0.5
	2015	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	2015	2.86	−2.46	0.40	0.09	0.11	0.09	628.00	0.46
	2016	3.21	−2.39	0.82	N/A	N/A	N/A	664.00	0.48
	2017	1.72	−2.42	−0.70	N/A	–	–	440.50	0.42
	Mean	**3.16**	**−2.42**	**1.34**	**0.09**	**0.08**	**0.08**	**724.80**	**0.44**
Glacier A Bravo	2011	2.49	−2.49	0.00	0.12	0.12	0.12	551.00	0.45
	2012	3.05	−1.25	1.80	0.11	0.13	0.12	684.00	0.45
	2013	1.89	−3.31	−1.41	0.11	0.13	0.12	423.00	0.45
	2014	2.17	−2.93	−0.77	0.11	0.14	0.12	473.00	0.46
	2015	3.56	−3.02	0.54	0.10	0.14	0.12	640.00	0.43
	2016	3.51	−2.60	0.87	N/A	N/A	N/A	800.00	0.44
	2017	1.52	−2.39	−0.81	0.11	0.12	0.12	396.00	0.40
	Mean	**2.60**	**−2.35**	**0.03**	**0.11**	**0.13**	**0.12**	**566.71**	**0.44**
Glacier A Charlie	2011	2.50	−0.54	1.96	0.02	0.03	0.02	590.00	0.42
	2012	3.43	−0.88	2.55	N/A	0.03	0.02	766.00	0.45
	2013	2.43	−2.24	0.20	0.02	0.03	0.02	545.00	0.45
	2014	2.11	−1.93	0.19	0.02	0.05	0.03	477.00	0.44
	2015	2.97	−1.74	1.22	0.01	0.04	0.02	650.00	0.46
	2016	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	2017	1.94	−1.45	0.49	N/A	N/A	N/A	465.00	0.44
	Mean	**2.69**	**−1.47**	**1.22**	**0.02**	**0.03**	**0.02**	**605.60**	**0.44**

WY 2010–2017 winter balances ranged from 0.47 m w.e. at the lowest site, Exit Alpha, (WY 2014) to 3.85 m w.e. at the highest site, Exit Delta, (WY 2014) (Figure 9). It is likely that these opposite extreme winter balances occurred in the same year because of a higher freezing line during the warm winter that led to low-to-no snow accumulation and/or snow persistence at low elevations. This highlights the importance of temperature vs. precipitation for accumulation/snow persistence.

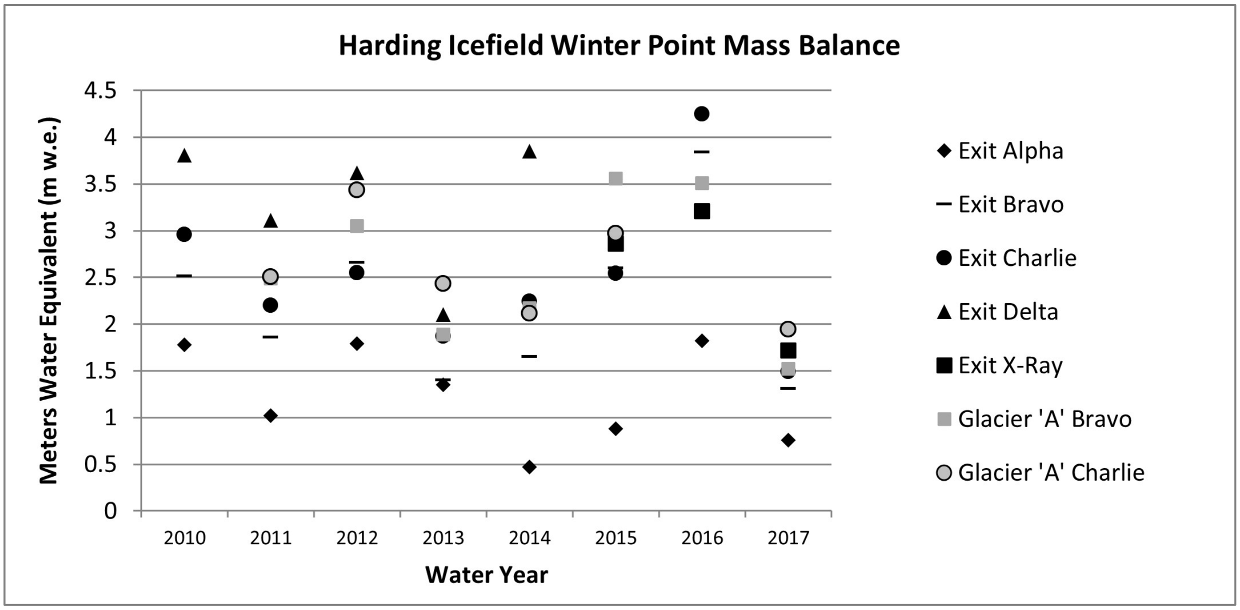

Figure 9. Winter point mass balance, WY 2010–2017. NPS / DEB KURTZ

WY 2010–2017 summer point balances range from −0.54 m w.e. at Glacier A Charlie in WY 2011 to −8.35 m w.e. at Exit Alpha in WY 2015. All sites are trending down, indicating greater negative summer balances and more ablation during the summer at all elevations (Figure 10).

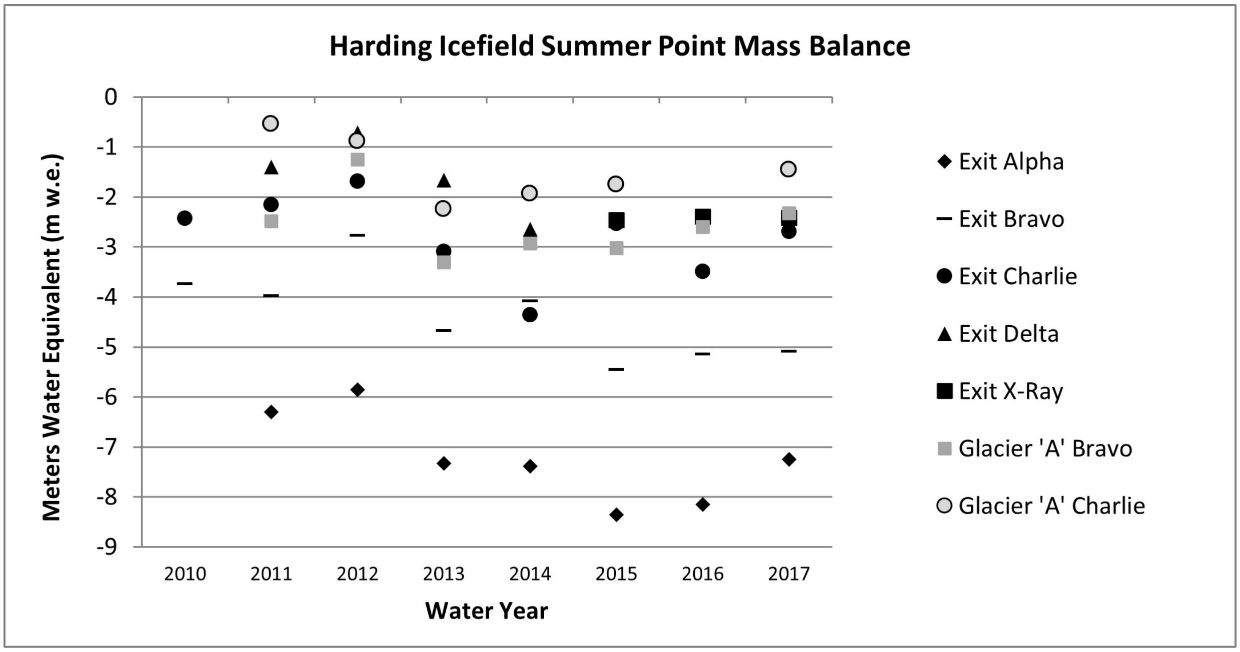

Figure 10. Summer point mass balance, WY 2010–2017. NPS / DEB KURTZ

Annual point mass balances vary from year to year at each site (Figure 11). As expected, the sites at the lowest elevations (in the ablation zone) have the most negative balances, and the sites at higher elevations (in the accumulation zone) have positive or nearly neutral balances. Annual point mass balances are trending down through time, indicating increased mass loss at all sites except Glacier A Charlie. Glacier A Charlie has maintained positive annual net balances but the amount of gain has been decreasing.

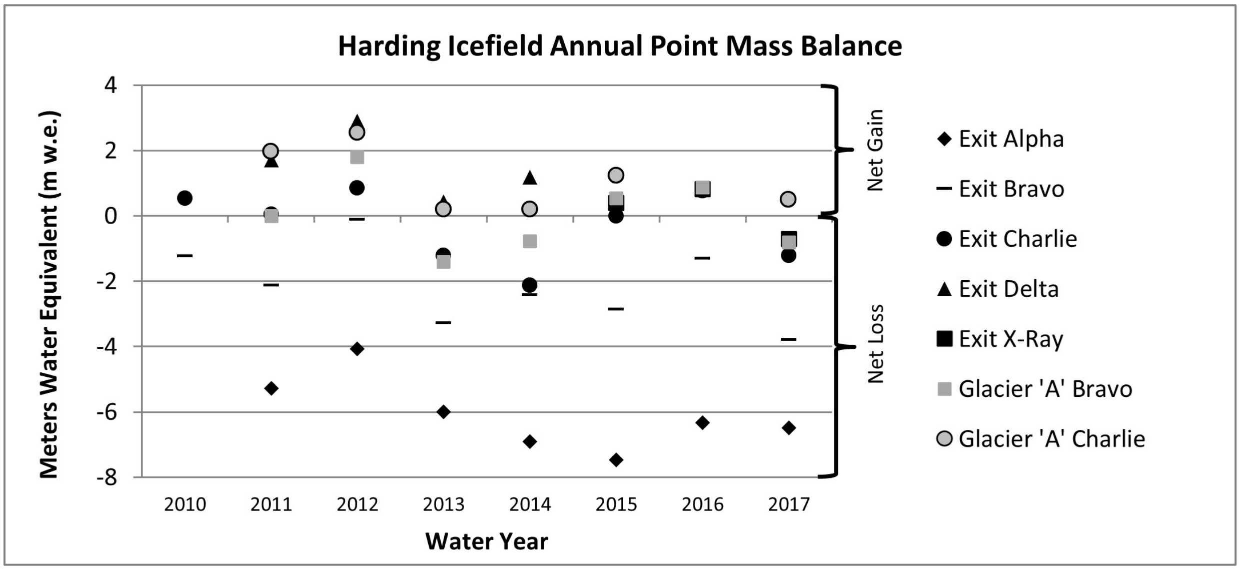

Figure 11. Annual mass balance at each site on the Harding Icefield by water year. NPS / DEB KURTZ

The annual balance at Exit Alpha, the site located at the lowest elevation, ranges from −4.06 m w.e. (WY 2012) to −7.47 m w.e. (WY 2015).

Glacier "A" Charlie, the site at the highest elevation with the most consistent measurements, has a range of annual balances from 0.20 m w.e. (WY 2013) to 2.55 m w.e. (WY2012).

Exit Delta, the highest site in the project, had the greatest annual balance of 2.9 m w.e. (WY 2012) during the observation period from 2011 to 2014. Exit X-ray was established near Exit Delta with the intent to replace the data point lost when we discontinued measurements at Exit Delta in 2015. In 2015 and 2016, Exit X-ray had positive annual balances, but in 2017, it experienced a negative annual balance.

At the beginning of the project, Exit Charlie was located near Exit Glacier's estimated average ELA. Annual mass balance calculations from 2010 to 2017 support that estimate and indicate that Exit Charlie is most representative of Exit Glacier's ELA. Annual balances at Exit Charlie range from −2.12 m w.e. (WY 2014) to +0.86 m w.e. (WY 2012) with two years indicating nearly no annual change at this site (+0.05 m w.e. and 0.00 m w.e. in 2011 and 2015, respectively). Cumulative balances at Exit Charlie shifted from positive to negative in WY 2014. This was apparent during the WY 2014 summer balance site visit when the three pieces of plywood that had been marking the three summer surfaces from the previous positive balance years (WY 2010, 2011, and 2012) were all exposed and stacked on top of each other with no snow between them (Figure 12).

Figure 12. The stake at Exit Charlie in September 2014. The plywood representing the summer surface from three positive balance years, WY 2010, 2011, and 2012, are stacked up together after all firn from these years melted completely in WY 2014. Notice the insulating effect of the stacked plywood. The plywood was removed, the summer surface was leveled to represent the surrounding surface, and one piece of plywood was relabeled and returned to mark the WY 2014 summer surface. NPS / DEB KURTZ

All sites lost mass throughout the study. The rate of loss at the two lowest elevation sites, Exit Alpha and Exit Bravo, steadily increased throughout the study, while sites at higher elevations did not experience the same rates of change and experienced more interannual variability (Figure 13).

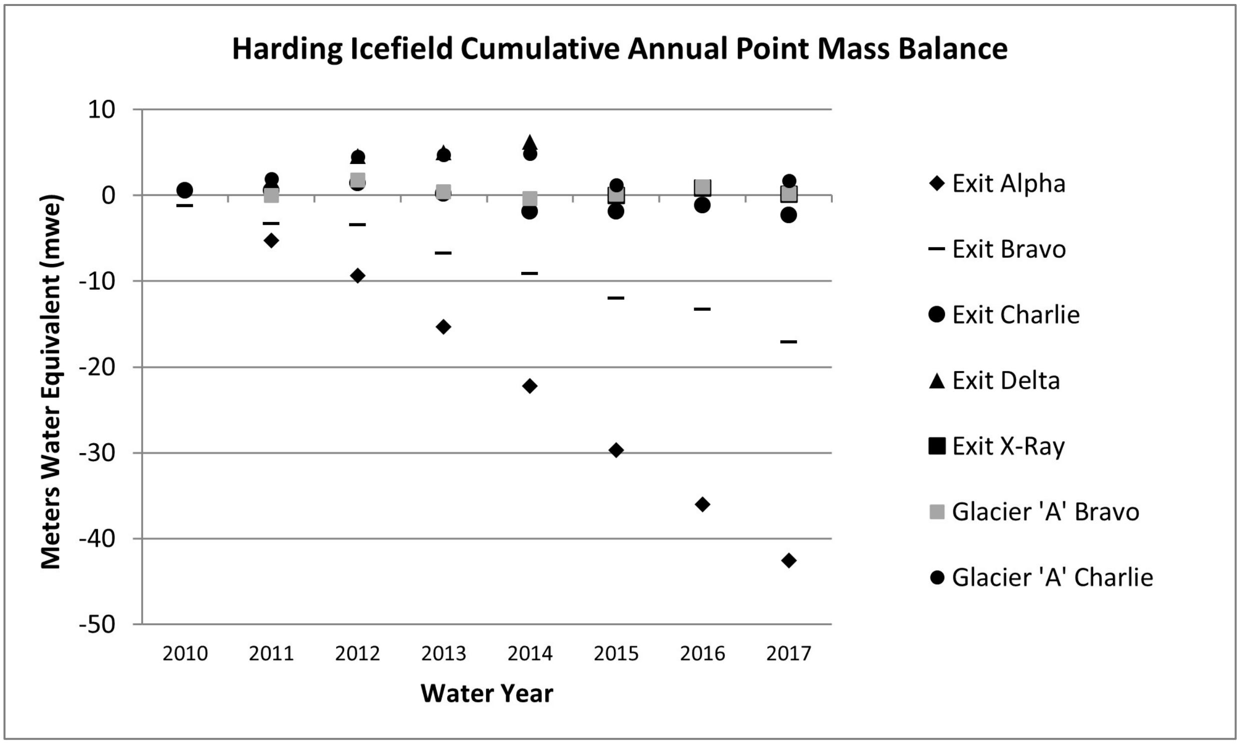

Figure 13. Cumulative annual balance at each site on the Harding Icefield by water year.
NPS / DEB KURTZ

Mass Balance Error Estimate

The mass balance error for these results (i.e., annual point mass balance) is estimated at ± 0.32 to 0.46 m w.e. based on that reported for four glaciers by Riedel and Larabee (2013).

Surface Elevation Change

Based on annual GPS measurements taken at the index sites at each fall measurement, the surface elevation has decreased at every site except one, Exit X-ray, the site at the highest elevation (Table 4). Sites at the lowest elevations experienced more rapid surface melt than the sites at highest elevations (Figure 14). This is consistent with the downward trend of mass balance reported above (Figure 13).

Table 4. GPS-measured surface elevation change at each site.

Site	Original Elevation (m)	Time period	Cumulative surface elevation change (m)
EXIT ALPHA	531.9	2009–2017	−27.3
EX B	866.7	2009–2017	−13.8
EX B—side	866.7	2010–2015	−10.7
EX B—center	800.1	2015–2017	−3.1
EX C	1111.0	2009–2017	−6.8
EX D	1290.0	2009–2014	−4.2
EX X	1248.8	2015–2016	0.4
GA B	1108.4	2010–2017	−9.7
GA C	1230.0	2010–2017	−6.5

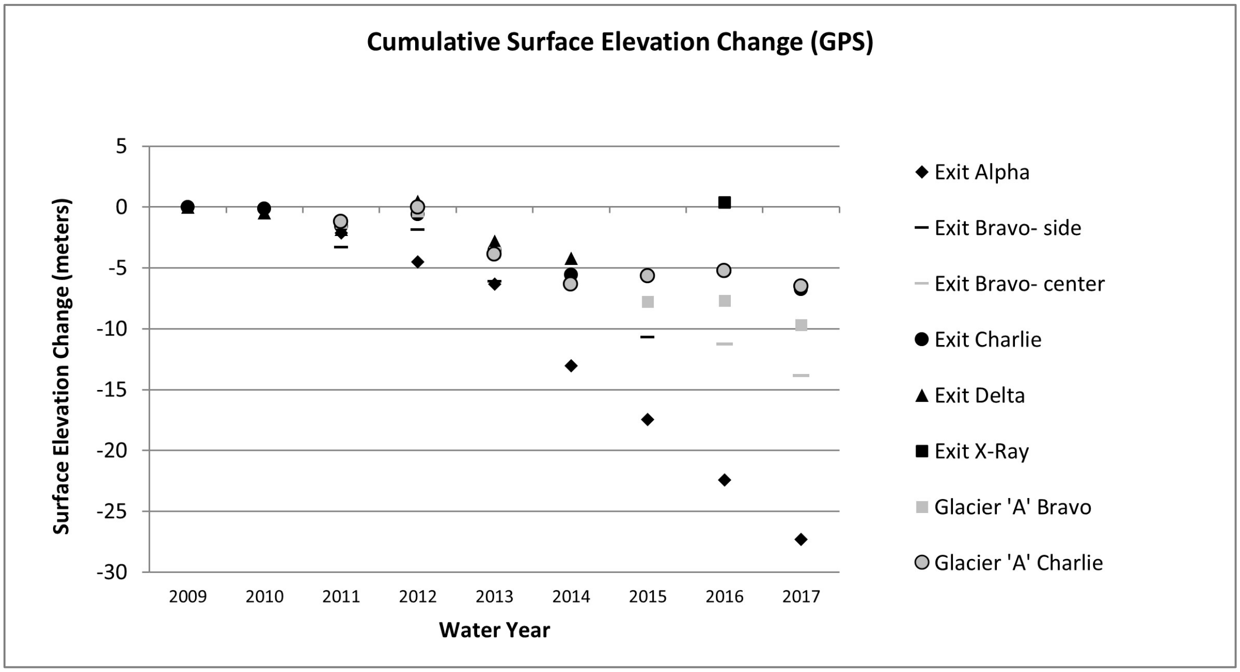

Figure 14. Surface elevation change measured in the fall at the stationary index site at each mass balance site on the Harding Icefield, 2010–2017. NPS / DEB KURTZ

Weather

Winter temperatures affect accumulation as the freezing level determines whether winter precipitation falls as snow or rain along Exit Glacier's elevation gradient. Comparisons of winter air temperature at Seward Airport, Exit Glacier SNOTEL, and the Harding Icefield RAWS can help determine the approximate location of the monthly freezing line. All three stations experienced an upward trend in air temperatures during the study (Figure 15).

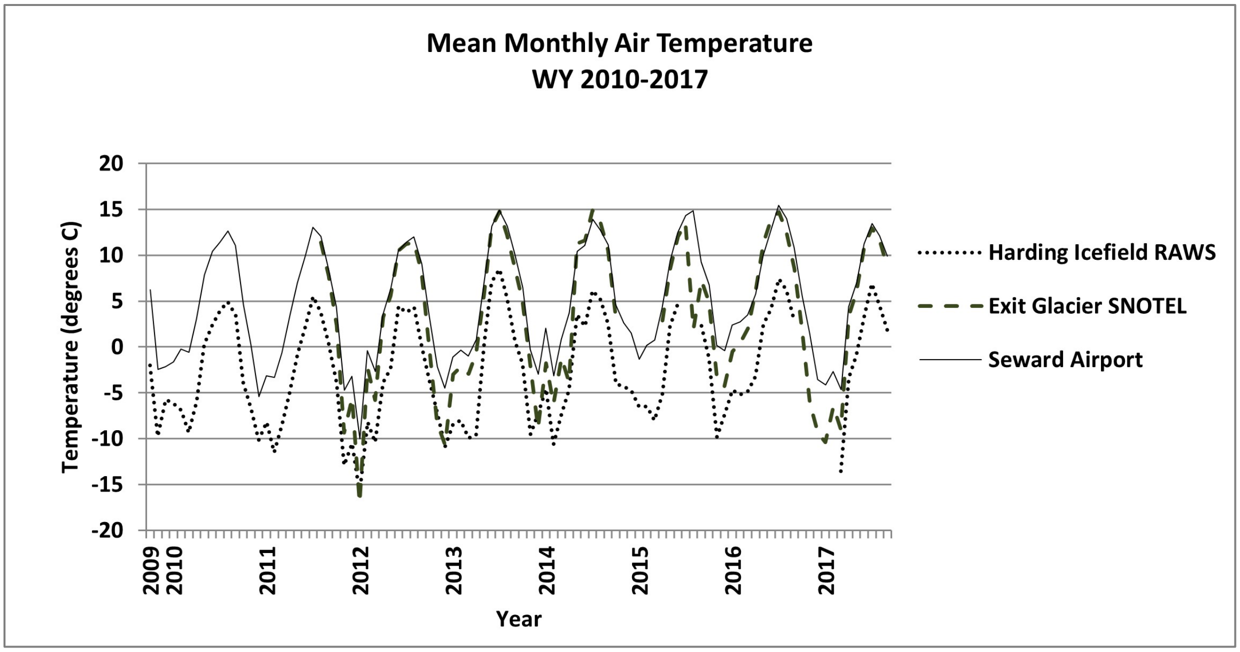

Figure 15. Mean monthly temperature at the Harding Icefield RAWS, Exit Glacier SNOTEL, and Seward airport for WY 2010–2017. Data from all three stations indicate an upward trend in temperatures for the eight-year period. NPS / DEB KURTZ

Figure 16 charts the total monthly precipitation recorded at the Harding Icefield RAWS, Exit Glacier SNOTEL, and Seward Airport, all close to Exit Glacier but located at different elevations and different distances from maritime influence. These weather stations can provide a general measurement of precipitation; however, the different sites are managed by different entities and may use different gages in general or different gages seasonally, reducing the ability to adequately compare stations. This is particularly an issue during winter storms that are accompanied by high winds that make measuring precipitation difficult. The northern Harding Icefield RAWS records less precipitation than the Seward airport station which is nearly at sea level and located near the shore of Resurrection Bay. The SNOTEL station may produce a more accurate precipitation measurement at its site as it is situated in an area that is generally more protected from winds.

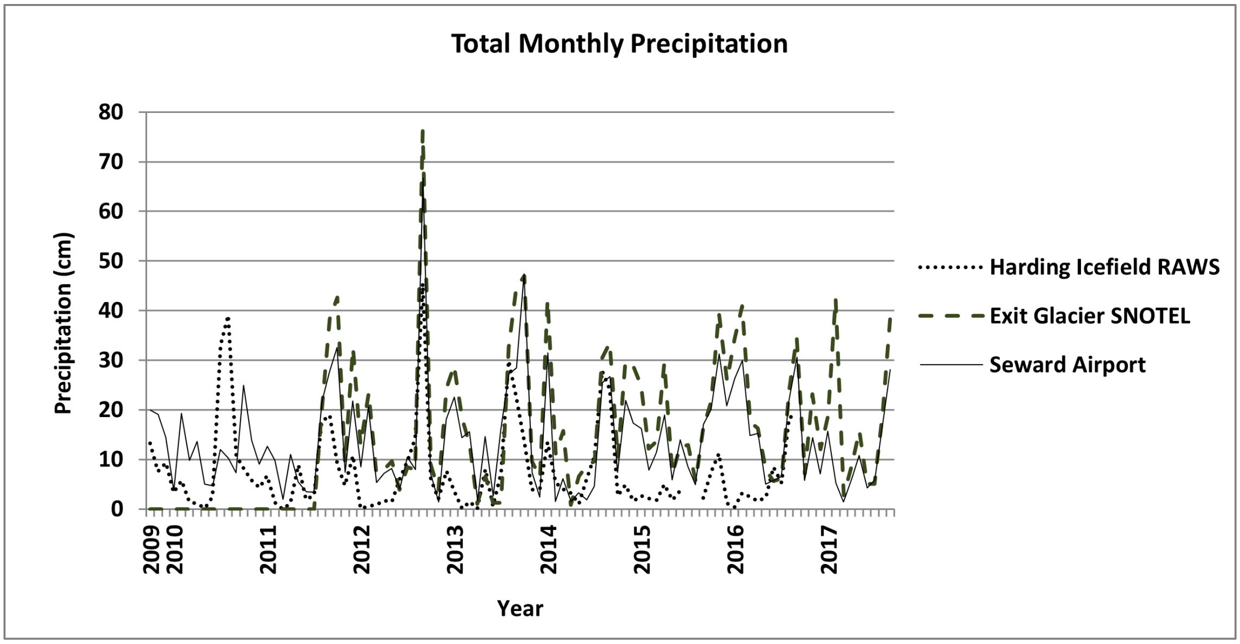

Figure 16. Total monthly precipitation at the Harding Icefield RAWS, Exit Glacier SNOTEL, and Seward airport for WY 2010–2017. NPS / DEB KURTZ

The large data spike in September 2012 is the result of significant rainfall received in the area when three major storms followed a similar path over the Kenai Fjords area bringing 66.75 cm (267% of normal) of rainfall to the Seward airport and 76.2 cm and 45.4 cm to the Exit Glacier SNOTEL and Harding Icefield RAWS, respectively.

The mean winter temperature from 2010–2017 was +0.30°C at the Seward airport. Winter 2017 temperature was not available at the Harding RAWS, but the mean winter temperature from 2010–2016 was −7.03°C. The mean summer temperature was 3.32°C at the Harding Icefield RAWS (data is unavailable for summer 2015) and 11.20°C at the Seward Airport. Overall, both winter and summer seasonal temperature data indicate an overall warming trend at both stations during the 2010–2017 period (Figure 17).

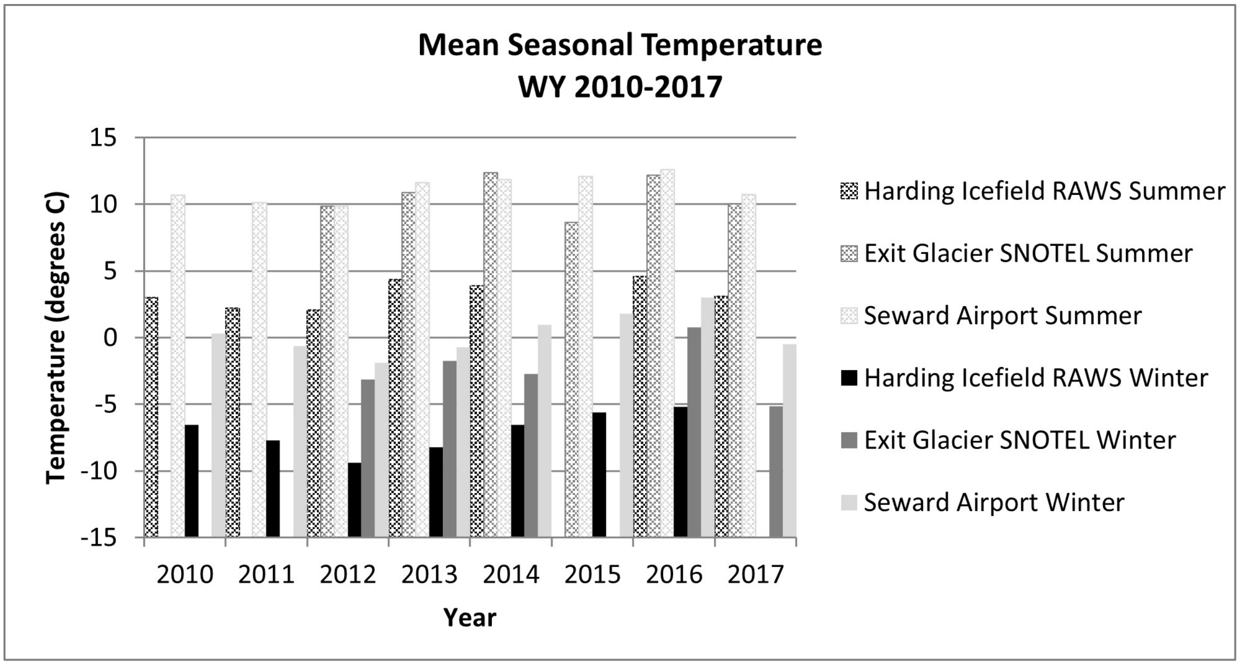

Figure 17. Mean seasonal temperatures at the Harding Icefield RAWS and the Seward airport near Exit Glacier, WY 2010–2017. Winter is defined as October–April. Summer is defined as May–September. NPS / DEB KURTZ

The issues of measuring precipitation and inter-site comparisons described above are particularly evident in the chart of seasonal precipitation (Figure 18). However, it may be useful to compare precipitation at a single site through time.

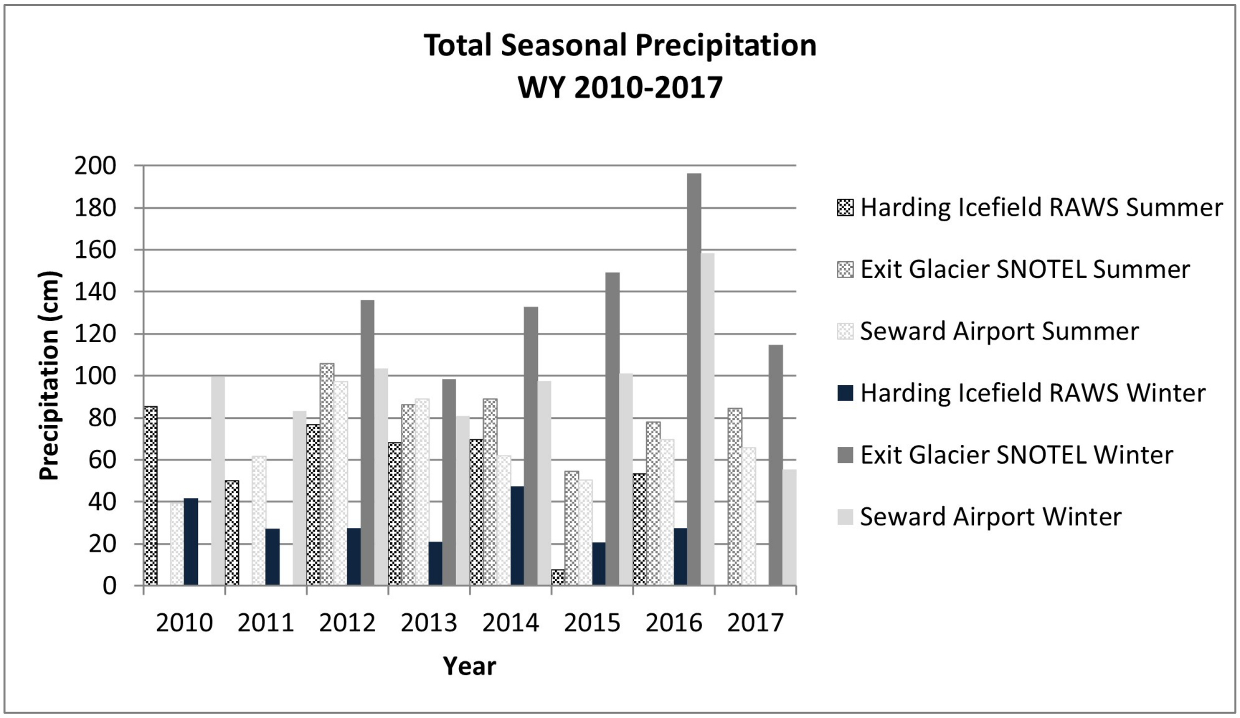

Figure 18. Seasonal precipitation totals for the Harding Icefield RAWS, the Exit Glacier SNOTEL, and the Seward airport for WY 2010–2017. The SNOTEL station was installed in summer 2011. Winter is defined as October–April. Summer is defined as May–September. NPS / DEB KURTZ

Discussion

The main objectives of this project were to describe and summarize point mass balance measurements on the northern Harding Icefield. Data include both seasonal and annual measurements of snow/ice accumulation and ablation. The resultant dataset provides eight years of point mass balance measurements, filling a large spatial data gap in field measurement of glaciers on the Kenai Peninsula. The addition of this dataset into the World Glacier Monitoring Service database will allow it to be easily utilized in a variety of larger regional and global studies related to climate change and sea level rise. Others may utilize them as valuable in-situ data for validating and calibrating models and remote sensing analyses.

Results of this project indicate persistent and increased loss of glacial mass on the northern Harding Icefield, particularly at lower elevations. This is consistent with results from other mass balance studies, both local (O'Neel et al. 2019) and global (Zemp et al. 2019).

Warming Trend

In the past 60 years, the average annual air temperature in Alaska has increased by 1.7°C (3°F) (a rate twice that of the rest of the United States) and is predicted to rise by an additional 2°F to 4°F by 2050; the mean winter air temperature has increased by 3.1°C (6°F) (Chapin et al. 2014). Local weather stations recorded an upward trend in temperatures from the study period of 2010 to 2017 (see Figures 17 and 18). If these regional and global warming trends continue as expected, the warmer temperatures in the summer will speed up the downward trend of mass balance at all sites and increase surface-wide summer melt. Warmer winter temperatures are expected to lead to increased precipitation as warmer air masses can hold more moisture. This will affect winter accumulation differently at different elevations: there will be less accumulation below the freezing level where precipitation will fall as rain instead of snow whereas above the freezing line there could be an increase in accumulation. This may have been a factor in why Exit Alpha measured its lowest snow depth, and Exit Delta measured its highest snow depth in WY 2014 (Figure 8). As winter temperatures increase, the freezing line will also increase in elevation. Data from the Exit Glacier SNOTEL station show that the mean winter (October–May) air temperature from 2011–2016 was above 0°C on 51% of days (Kurtz and Baker 2016).

As stated earlier, snow and ice, the majority of which is flowing from the Harding Icefield, covers 48.5% of KEFJ (Loso et al. 2014). This half of the park has a very high albedo as snow can reflect nearly 90% of incoming solar radiation. As this mass of ice and snow shrinks, the immediate shift in landcover from snow/ice to bare rock/vegetation and or water affects the albedo of the local environment, resulting in increased surface warming as the low-albedo surfaces of rock, vegetation, or water will absorb more radiation than the snow/ice, causing an increase in temperatures in the local microclimates. This can result in a local positive feedback loop where less ice leads to lower surface albedo, which leads to warmer microclimates, which leads to increased melt along the snow/ice margins, which leads to less ice, and so on. KEFJ staff are anecdotally observing this effect at Exit Glacier, where the northern margin of the outflowing portion of the glacier has melted faster along the rocky south-facing slopes due to these edge effects.

Warming temperatures and continued negative mass balance offer the potential for a second positive feedback loop that could lead to greatly accelerated thinning of the Harding Icefield. The elevation of the central plateau of the Harding Icefield lies between 1,200–1,400 m a.s.l., and the thickest ice measured within this central area is 564 m deep (as of 2014) (Truffer 2014). This means that nearly half of the substrata that give the Harding Icefield its altitude is ice. As the icefield melts, its surface elevation decreases, exposing the icefield surface to warmer temperatures, resulting in greater melt in the summer and more potential for winter precipitation to fall as rain rather than snow, instigating a self-amplifying lowering effect. Eventually, the surface could decrease to an elevation below the ELA, where there is a negative mass balance across the entire icefield. This can (and with warming temperatures, likely will) lead to a positive feedback loop where melt leads to lower surface elevation, which leads to more negative mass balance, which leads to lower surface elevation, and so on. This cycle, first explained by Bodvarsson (1955) has been observed on the Yakutat Glacier and has been implicated in its "runaway thinning and retreat" (Trüssel et al. 2013).

Error

Multiple sources of potential error are identified in glacier mass balance measurements. Site visits are scheduled to approximate the minimum and maximum glacier-wide balances within a WY. However, the timing of these visits can vary slightly year-to-year due to weather and logistical constraints. This means that the mass may not be at its maximum or minimum when the summer and winter measurements occur. Although the associated error is: (1) small relative to the overall signal and (2) accounted for when estimating long term trends in mass balance, we suggest that, in the future, weather data be modeled to incorporate any post-measurement additional accumulation or melt to evolve these data from measurement date mass balances to modeled mass maxima and minima. This would allow them to be presented in both the measurement date time system and the stratigraphic system (Cogley et al. 2011).

Field measurements collected from 2010 to 2016 may include variability in snow probe depths (often due to ice lens layers common in the maritime snowpack) and inaccurate stake height and snow density measurements. Leaning and or bent stakes that are unable to be straightened in the field require trigonometric calculations to determine surface elevation along the stake, sometimes with an assumption of where the stake bent below the snow surface. Using a mapping grade GPS unit provides 10–100 cm (typically <50 cm) post-processing accuracy, while the combination of high latitude and high local terrain can challenge the acquisition of good satellite geometry for GPS mapping.

Numerous low-pressure systems often pass through the northern Gulf of Alaska in September, bringing high amounts of precipitation. Temperatures often fluctuate above and below freezing on the Harding Icefield leading to a heterogenous series of freeze-thaw and accumulate-melt events that can make it difficult to distinguish the strata at higher elevations during the fall measurement. For example, during the fall measurements at Exit Charlie and Exit Delta alone, we have observed solid ice, firn, previous winter's snow, fresh snow, windblown fresh snow, ~16 cm of slush, frozen slush, and various combinations of these strata. This can complicate our ability to identify the surface to measure. Plywood at the previous summer surface can help identify the previous fall's surface. If there isn’t plywood at the site, examination of the crystalline structure could help, but there often isn’t sufficient time for that when we only have a helicopter for one day.

Glacier monitoring requires long-term data collection to understand annual and decadal weather patterns such as the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) that can obscure long-term trends if assessed in the short term. Eight years is a small window of monitoring and other studies with larger timeframes have determined that the Harding Icefield is shrinking (Giffen et al. 2014; Loso et al. 2014; Rice 1987) and thinning (Larsen et al. 2015; Loso et al. 2014; Arendt et al. 2002; Adalgeirsdottir et al. 1998; Sapiano et al. 1998; Van Looy et al. 2006). Exit Glacier’s terminus has retreated 0.44 km during the mass balance study period (fall 2009–fall 2017) (Kurtz and Baker 2016). Mass balance data and repeat photography provide both quantitative and qualitative observations of decreasing surface elevations, particularly at Exit Alpha.

Recommendations

For the 2010–2017 mass balance data:

- Conduct a systematic assessment of measurement errors.
- Compile weather data and model additional accumulation or melt that may have occurred following each seasonal measurement.
- Compile aerial photos and/or satellite imagery to develop annual glacier outlines and incorporate these outlines with the mass balance data to interpolate annual glacier-wide balances for Exit Glacier.
- Submit the data to the World Glacier Monitoring Service and Global Land Ice Measurements from Space (GLIMS) glacier databases.
- Strategize how to continue in-situ point mass balance measurements on Exit Glacier to provide a greater basis from which glacier health and impacts of climate change can be studied. Consider the value of reducing measurements to 1–2 sites accessible by foot and identify locations that would provide the most meaningful data.

Future considerations:

- Incorporate geodetic methods (i.e., DEM differencing) to quantify annual areal, surface, and volume change on Exit Glacier.
- Host a glacier monitoring workshop with participants from NPS, USGS, USFWS, and academia to assess KEFJ’s previous and ongoing glacier monitoring efforts and results and determine how the park’s efforts should proceed. Some topics to consider include:
    - Identify additional glaciers for annual geodetic surveys. The Harding Icefield’s spatial asymmetry affords an opportunity to measure mass balance on different types of glaciers within different types of climates in a relatively localized geography. This provides opportunities to interpret glacier sensitivity to climate and the influence of terminus geography on mass balance and geometry (and vice-versa).
    - Identify opportunities to share resources (e.g., staff, helicopter flights, equipment) for efficient and cost-effective glacier monitoring efforts.

Conclusions

Glacier mass balance trend analyses require long-term datasets. Eight consecutive years of seasonal data provide insight into the health of the northern part of the icefield and a base to build on with continued measurements. The contribution of this dataset to world repositories of mass balance fills an important spatial hole and can provide highly valuable points of comparison with other longer-term datasets. Continued mass balance measurements would provide a greater basis from which glacier health and impacts of climate change can be studied.

Exit Glacier and the northern Harding Icefield are experiencing direct impacts of climate change, resulting in persistent and increased mass loss, particularly at lower elevations where surface melt has led to significant thinning and retreat of Exit Glacier. Management implications related to this include impacts to infrastructure (primarily trails), reduced access to the glacier, resulting in logistical challenges to monitoring and reduced visitor appeal, and increased safety concerns related to glacier-related geohazards. These impacts will persist and speed up in process and/or frequency unless there is a significant change in climate trends.

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Appendix A: Seasonal Data Collection History

This appendix provides an administrative history for each season's site visit beginning with the winter stake extension, followed by the spring accumulation measurements, and ending with the summer balance measurements.

WY 2010

WY 2010 was the first year of mass balance measurements on Exit Glacier, beginning with stake installations on Exit Glacier in Fall 2009. The only stake that was located during the spring site visit was Exit Alpha. Exit Bravo, Exit Charlie and Exit Delta were not recovered. Snow density was measured at all sites. Snow depths at Exit Charlie and Exit Delta are crude estimates. In blizzard conditions the field crew dug pits and probed but the depths exceeded the length of the probe (5.6 m).

Summer balance measurements were not possible during the fall site visits at Exit Alpha and Exit Delta. The stake at Exit Alpha had fallen out of the ice. The stake at Exit Delta was located under 1.2–4 m of snow on top of the previous year's surface. Mass balance was not calculated for sites Exit Alpha and Exit Delta.

WY 2011

Mass balance stakes were extended during a mid-winter site visit on February 5.

During the spring site visit probe depths and density measurements were taken at all four sites on Exit Glacier and the two new sites on Glacier-A. Stakes at Exit Bravo, Charlie and Delta were leaning and required trigonometric calculations to determine snow depth based on stake height.

All sites were measured in fall 2011. New snow was observed at all sites except Exit Alpha and Exit Bravo. The new snow was removed for WY 2011 measurements and returned to the site for inclusion in WY 2012 measurements.

WY 2012

A mid-winter stake extension was attempted via helicopter on February 24, but ground fog on the northern Harding Icefield prohibited access to the sites.

Because the stakes were not extended in the middle of the winter, it was anticipated that the stakes would be buried, and we wouldn't be able to locate them in the spring. To assist with their relocation, we calculated their expected location based on the previous fall position and measured flow velocities and trajectories in ArcGIS and entered the calculated points into a Garmin GPS for navigation. In the field, we found that all stakes were buried. Exit Alpha, Exit Charlie, Glacier-A Bravo and Glacier-A Charlie were easily located with the pre-calculated locations in the GPS and a metal detector. Therefore, the stakes were available for measurements and a pit was dug at each site. Exit Bravo was not located. A pit was dug and a new stake was installed at this site for cross-referencing with the existing stake in the fall. Exit Delta was not located but we dug a snow pit was dug and probed snow depths. Rare earth magnets placed in the tops of all stakes except Exit Alpha and Exit Bravo in fall 2011 enabled the metal detector to detect the stakes quicker.

WY 2012 snow depths were based on stake heights. No probing below the pits was done at any of the sites.

September 2012 was an unusually wet month in KEFJ. As recorded at the Seward airport, total precipitation for the month was 26.3 inches (267% of normal), 16.4 inches above the 30-year average (1981–2010) for the month. Rain was recorded at the Seward airport 26 of the 30 days of the month, making it impossible to fly to the icefield in a helicopter for summer balance measurements until the second week in October. Although the precipitation was rain at sea level, some of it fell as snow at higher elevations where up to 1.1 m of snow accumulated at sites above 1250 m. This snow was shoveled to the side for WY 2012 measurements and was returned to the site for the WY 2013 spring measurements. Stake heights were recorded and WY 2012 snowpack was measured at all sites.

WY 2013

There was no mid-winter site visit in 2013 to extend the stakes.

Spring stake locations were calculated based on fall positions and flow velocities and trajectories in ArcGIS and entered into a Garmin GPS to assist with locating them. Exit Charlie was the only stake not completely buried by the winter accumulation. All stakes except Glacier-A Charlie were leaning and required a trigonometric calculation to determine stake height. Snow depths were based on trigonometrically corrected stake heights. Snow was sampled for density measurements at all sites.

The fall site visit did not occur until late October due to weather delays in September and a three-week government shutdown beginning October 1st. A late-season site visit like this is not ideal as there is less daylight to work in and more new snow to remove prior to taking measurements.

Despite the late date for the fall measurements, we were able to successfully measure winter balance at all six sites at the end of October. All sites except Exit Alpha (the lowest elevation) had new snow. This prevented us from observing and documenting what may have been one of the highest annual ELA extents on the icefield in recent years (and certainly during the history of this project). The new snow, which will be measured as part of WY 2014 winter balance, was removed at each site (up to 5.5 m) so measurements of the start/end WY could be recorded. The record warm temperatures of summer 2013 resulted in the lowest summer balance and lowest annual balance to date at each site on Exit Glacier (except Exit Alpha). At the lowest site (Exit Alpha), we measured a loss of 6.65 m of surface ice (.5 m melted in September alone). Farther up the glacier at Exit Charlie (elevation 1,111 m) there was a loss of 1.36 m of surface ice. Perhaps even more notable at this site was the observation that, in addition to the WY 2013 accumulation melt, all firn that had accumulated since the project started in fall 2009 also melted in WY 2013.

WY 2014

All stakes except Exit Alpha were extended in February 2014 on a shared helicopter flight with USGS.

All stakes were easily located in the spring of 2014, because of the extensions that were added in February. Since the stakes were extended and it appeared that it would be a low snow year, we anticipated being able to find all stakes and, therefore, chose not to bring the steam drill.

The ski down from Exit Alpha, which we do every year, was on thinner snow than usual, and resulted in greater exposure of crevasses and required greater considerations for route-finding. This reinforced and emphasized the requirement of glacier travel and crevasse rescue skills and safety equipment. The snowpack was thin (1 m) at Exit Alpha and diminished to bare ice as we descended the center of the glacier toward the terminus. Exposed ice on the lower portion of the glacier (below Exit Alpha to the outwash plain) necessitated that we trade skis for crampons and walk, requiring three trips to transport all gear and equipment off the glacier.

In spring 2014 we did not record index site GPS data for the sites to streamline data collection and minimize field time (particularly since the first two or three sites are conducted while a contracted helicopter waits for us). Since the surface change is only measured from fall to fall, we decided to eliminate this step in the spring fieldwork going forward.

Based on USGS recommendations, in spring 2014 we tried to sample the entire snowpack at all Exit Glacier sites using the Kovacs corer with a power drill. We found this very time-consuming and difficult to do. The cores came out in multiple pieces that had to be measured and weighed individually along with loose granular snow. Our confidence in our ability to recognize granular snow in the snowpack from granular snow from the collapse of the core walls was too low to trust any of these additional measurements so we did not include them in the final measurements. This additional step also significantly increased the amount of time it took us to sample each site.

Due to the numerous thaws and rainstorms that occurred on the icefield during the WY 2014 winter and spring, there were several ice layers in the snowpack. This also increased time needed for measurements and made shoveling difficult and probing impossible at the two sites on Glacier-A. Snow depths were based on stake heights at these two sites.

The fall 2014 helicopter-based site visits occurred on September 23rd for all sites except Exit Alpha which was accessed on foot and measured on September 24th. Inadequate weather prevented us from flying until the week of September 21st.

In fall 2014 we installed a temporary stake (Exit X-ray) slightly below Exit Delta. Depending on results of the winter balance measurements at this site, Exit X-ray could potentially replace Exit Delta as a more representative site for this elevation. Exit Delta is the most problematic site and takes the longest amount of time, both in the spring and the fall, to measure. It is the highest elevation, and it seems to receive the most wind (from the Gulf of Alaska, funneled by Bear Glacier and through the nunataks) based on observations of the stake leaning and/or being broken. There is also a question as to whether this site is in a perennial snowdrift. Although a snowdrift adds to the balance of a glacier, it is not representative of all locations in the upper elevations (although, many other locations at this elevation are scoured by wind, which may not be entirely representative (or represented) either). To remedy this influence and to make data collection at this site more efficient and reliable (we often cannot find the stake in the spring), we inserted a stake at a new site, Exit X-ray, slightly down-glacier from the existing Exit Delta above 1250 m (the existing stake is at 1290 m). These two stakes will be compared in the spring. The new site had 6 cm of new snow that was removed and returned on top of the plywood that was placed down. The summer surface was apparent due to a dirty, icy layer.

The stake at Exit Delta was standing but significantly bent. After shoveling a 1 m pit, it was still difficult to identify layers indicative of a summer surface. We cored approximately 1 m to the plywood on the WY 2013 summer surface and still saw no layers or discolored snow such as we saw at the firn surface (remaining winter balance from the previous WY) at Exit X-ray and determined that the 2 m of snow at this site was firn. Since it was impossible to identify new (September) snow (which may be <10 cm based on Exit X-ray), we measured all of it as WY 14 winter balance. This is a potential source of error.

Glacier-A Bravo had no remaining WY14 firn and had a small pedestal of ice under the plywood, indicative of insulation. We tried to chip this ice down to the surrounding surface. Due to time constraints, we did not walk to the index site to measure it.

Exit Charlie was easily located with three pieces of plywood piled together on a pedestal of ice (formed as surrounding ice melted faster than ice below the plywood which acted as insulation from the sun). We chipped away most of the ice pedestal to be flat with the surrounding ice surface. Some of this pedestal formed in summer 2013 but we did not have time to chip at it in fall 2013.

Exit Bravo was the last site visited during the helicopter-based fall measurement. In the past few years, there has not been enough time to do everything we would like to do at this stake (in fall 2013 we did not have time to insert a new stake. In fall 2014, we did not have time to relocate it closer to the center of the glacier where it is better for landing a helicopter.)

Due to insufficient time, the Exit Bravo index site was not measured.

Exit Alpha was visited in mid-summer to remove a section of stake. At this time, the 3 and 6 m sections of the stake were not joined together as a single stake, they were side-by-side in the hole. It appeared that someone had tugged on the stake and pulled them apart. Since the 3 m section was below the surface of the ice more than a meter, it was impossible to take a measurement. At the fall visit, both stakes were still next to each other but both were emerged. The 6 m stake was about .3 m below the 3 m section. It appeared that the dowel on the 3 m section prevented/slowed self-drilling, but the 6 m section did not have a dowel and, therefore, self-drilled more than the other section.

WY 2015

Winter

Only half the stakes, Exit Bravo, Glacier-A Bravo and Glacier-A Charlie were extended on February 2nd with assistance from USGS. Exit Alpha, Exit Charlie, and Exit Delta were not located.

Spring

Winter 2014–15 brought above normal temperatures and no snow at lower elevations. Due to the difficulties encountered descending Ext Glacier in low snow the previous year, we decided to visit each site by helicopter over the course of two days.

All winter balance measurements were completed. Although most of winter 2014–15 saw little to no snowfall near sea level, the mountains around Seward received 1–2 m of snow in the weeks leading up to the measurement. This made for interesting snow pits as there was more snow than was expected, but it was fresher and less compacted than is typical for the end-of-season snowpack. The warm temperatures throughout winter left several ice layers in the older/deepest snow depths which made digging and sampling the snow pit more difficult and time-consuming than usual.

The stake at Exit Charlie was not located during the spring visit. A snow pit was excavated at the location of the calculated stake location. The total depth of the snow pit, 315 cm, was sampled and cored. A new stake was installed for cross-referencing in the fall.

Just over half of the 664 cm of snowpack located at Exit X-ray was sampled. All the sampled snow had accumulated since the February stake visit.

The stake at Glacier-A Bravo was visible upon arrival. Based on stake math, there were 640 cm of snowpack, but probing indicated 570 cm. The inability to probe through an ice layer is the likely cause of the discrepancy. 640 cm was used for mass balance calculations.

The stake at Glacier-A Charlie was not located during the spring visit on May 1st. A snow pit was excavated and sampled to 310 cm (slightly less than half of the probed depth). It appeared that all the snow that was sampled was new snow that had fallen in April. Two new stakes were installed for cross-referencing. “GA_15_C_3m” detached from its 6 m section so a second stake, “GA_15-2_C” was installed.

Fall

The weather window for flying to the sites for the summer balance measurements began earlier this year to improve our chances of visiting the sites before new snow accumulated and to avoid snow bridges. The window was established for September 1–30. August was very dry with only 34% of normal monthly precipitation at the Seward airport. Measurements on the icefield were completed on September 19th and September 24th. Two days of flight time were scheduled this year for measurements and to move stakes back to their respective index sites to try to prevent them from flowing into crevasses and/or to keep them relatively near the index site.

The site visit to Exit Alpha occurred on October 1st. The 2014 stake was leaning significantly (with the base of the stake down-glacier from the top) and couldn’t be straightened so stake height was calculated with trigonometry.

While hiking from the Harding Icefield Trail to the edge of the glacier the coupler required to merge two sections of the Heucke steam drill hose fell off the hose, preventing us from putting in more than

7.68 meters of stake into the ice. This is inadequate to measure total ablation next year. A second stake will need to be installed to cross-reference this stake as surface melt will likely exceed this depth and the stake will melt out completely.

During the fall 2014 visit, we decided that we needed to relocate Exit Bravo to a location with a smoother surface and lower-angle slope for continued helicopter access to this site. The original location had become too steep to safely park the helicopter without the risk of it sliding. The ice surface in this area had also become very rough, adding to the challenge of landing in a helicopter. The center of the glacier looked like a more suitable site. We mapped the existing index site for the last time and then installed a new stake in the center of the glacier. The position of this new stake will serve as the new index site for future measurements of Exit Bravo.

Exit Charlie had 10 cm of fresh snow and three stakes protruding from the ice upon arrival. The main stake we wanted to measure in WY 2015 was lying almost horizontal to the glacier surface. It had lost the plywood that was placed on the fall 2014 surface and the top section of stake! We believe that the lack of snow and typical early winter high winds may have lifted the plywood onto edge causing the stake to bend. This allowed the plywood to become perpendicular to the winds which bent the stake nearly parallel to the ice surface and allowed the wind to blow the plywood off the stake, possibly ripping the duct tape holding the top section with it. Due to a light layer of fresh snow, we were unable to see the plywood or the top 3 m of stake. We straightened this stake and removed as many sections as we could, leaving 6 m in the ice.

We measured and then completely removed the cross-referencing stake installed in spring 2015.

A new stake was installed at the Exit Charlie index site.

Although Exit Delta was not located in the winter or spring WY 2015 visits, it was visible during the fall visit, and it was leaning significantly. We tried to remove at least a section of the stake but were unsuccessful. This site is being replaced by Exit X-ray. We should continue to monitor this site and remove stakes if/when they appear.

The stake at Glacier-A Bravo has been the most consistent site of the study. There have been no issues with the stake bending, breaking, or getting lost since it was installed in 2010. For this reason, the stake had not previously been cycled back to the index site. In fall 2014, the stake was surrounded by large crevasses that made travel to the index site trickier and riskier. During the fall site visit on September 19, 2015, we took a final measurement of this stake and then inserted a new one slightly above the index site (there was a crack at the index site).

Upon arrival, in fall 2015, the stake at Glacier-A Bravo had the plywood from the fall 2014 measurement, but the plywood had lost its white paint. Pictures from the previous year confirmed that it had been painted white. It is possible that the lack of early season snow kept the plywood exposed longer into winter than previous years and the paint was scoured off by winds carrying ice granules across the surface. Without the white paint, the plywood apparently retained more heat and into the glacier surface. At first, we thought that the strata at this site was ice (older than winter

2014–15) and that there was total ablation at this site in WY 2015. However, when we were at the index site drilling a hole for the new stake, we determined that there were 70 cm of firn at this site, which means that it was likely firn that the plywood had melted into. Since we had “hopped” to the index site in the helicopter, we measured the firn at the index site, not at the stake. The depth of firn at this site was later corroborated by the firn that was measured at Exit X-ray, a site that is similar elevation as Glacier-A Bravo.

WY 2016

Winter

Warm temperatures and above average precipitation in early winter resulted in little to no snow at lower elevations and above average snow at higher elevations. USGS reported that their stakes on Wolverine required extending in December and recommended that we not wait until February to extend our stakes. We (Chad Hults (AKRO) and Louis Sass (USGS)) tried to fly in January to extend our stakes, but weather prevented us from flying until late February. At that point, every stake was buried. Only one, Exit Charlie, was located with a metal detector and was extended.

Spring

Winter 2015–16 brought above normal temperatures and no snow at lower elevations. Due to the challenges, we encountered descending Exit Glacier on skis in low snow the previous year, we decided to visit each site by helicopter over the course of three days.

Although most of winter 2015–16 saw little to no snowfall at low elevations, the mountains around Seward received abundant snowfall. We were only able to locate two of the stakes during the spring site visit, Exit Charlie and Exit Alpha. At Exit Bravo we were able to probe to ice. At Exit X-ray, Glacier “A” Bravo and Glacier “A” Charlie we installed temporary stakes to allow us to crosswalk the stake heights in the fall once the existing stake was visible.

Fall

The weather window for flying to the sites for the ablation measurements was established for September 9–October 9. September 10 provided perfect weather for flying. There was no new snow at any of the sites.

Exit Alpha was visited on May 14th. This stake was visible upon arrival. The entire snowpack was sampled with a Norwegian tube and Kovacs corer.

There were three mid-summer site visits to Exit Alpha this year to monitor melt to ensure the stake didn’t melt-out completely.

The summer ablation site visit to Exit Alpha occurred on September 19th.

Exit Bravo was visited on May 13th, but the stake was not located. Snow depth was measured with multiple probes and half of the snowpack was sampled for density measurements. The fall site visit to Exit Bravo occurred on September 10th.

The spring site visit to Exit Charlie occurred on May 13th. The stake was extended in the winter and was observed upon landing. The fall visit occurred on September 10th. There was no new snow at this site allowing for an efficient fall measurement of remaining firn.

Exit X-ray was not located during the spring visit. A new stake (EX_X_16spr_6m) was installed to crosswalk with the existing stake in the fall. The top three meters of the snow were measured. Two stakes, EX_14_X and EX_X_16spr_6m were both located (very close to each other) in the fall. Both stakes were measured and all of EX_X_16spr_6m was removed. We attempted to measure all the firn but a large icy core would not detach (probably frozen to the plywood).

The spring site visit to Glacier A Bravo occurred on May 14th. The stake was not located during the spring visit. A new stake (GA_B_16spr_6.5m) was installed to crosswalk with the existing stake in the fall. The top three meters of the snow were measured. Both stakes were located and measured in the fall. GA_B_16spr_6.5m was removed and all firn was sampled.

Glacier A- Charlie was not located during the spring visit on May 15th. A snow pit was excavated and sampled to 300 cm. A new stake (GA_C_16spr_9m) was installed to crosswalk with the existing stake in the fall. The top three meters of the snow were measured.

Glacier A Charlie was visited for ablation measurements on September 10th. Upon arrival, the only stake visible was GA_C_16spr_9m. Despite searching with a metal detector, we did not find GA_12_C.1_16.5m. Therefore, we have no snow depths nor mass balance measurements for WY 2016 for this site. This stake is also unrecoverable during the spring visit. We may want to consider making changes at this site.

WY 2017

Winter

WY 2017 winter was cold and dry. Monthly average temperatures from December through March were below normal with March seeing a −22.5 degree C departure from normal. At sea level the below freezing temperatures allowed snow that accumulated during winter storms in January and February to persist throughout the spring months, giving the sense that there was more snow at sea level than normal despite the low precipitation totals. Louis Sass at the USGS extended the stakes on the Harding Icefield during the USGS mid-winter stake extension effort on Wolverine Glacier on February 6, 2017. Stakes were located at only three sites, Glacier A Bravo, Exit Charlie, and Exit Bravo. Exit Alpha was not visited. Approximately 3 m of snow was on the ground at sites Glacier A Bravo and Exit Charlie. In comparison, Wolverine Glacier had approximately 4 m of snow at their sites located at similar elevations.

Spring

Due to low precipitation during the winter and the difficulties we encountered descending Exit Glacier in the two previous low snow years, we decided to visit each site by helicopter over the course of two days.

Stake locations were calculated using the previously determined flow vectors with average winter flow velocities. I also created a shapefile of flow path between the Fall 2016 stake position and the calculated spring 2017 position. Both the paths and calculated points were uploaded to a GPS to provide more direction for using the metal detector.

WY 2017 winter accumulation measurements for the KEFJ northern Harding Icefield glacier mass balance project were completed on April 17–18, 2017 by a three-person crew. All six sites were accessed with a Bell 206-L3 helicopter. Each site required less than 3 hours to dig and core up to a 1.5 m pit in which we recorded temperature and sampled (measured and weighed) snow using a Norwegian tube followed by snow cores to full depth using a newly acquired Kovacs coring system.

Because three of the six sites (Exit Bravo, Exit Charlie, and Glacier A Bravo) were located and extended by USGS during a mid-winter site visit they, along with Exit Alpha, were readily located during the spring visit. The two highest stakes, Exit X-ray and Glacier A Charlie, were not located and extended in February or during the April visit. Accumulation was measured at the location of these sites and temporary stakes were installed to cross-reference the existing stakes when they emerged from the snow at the end of the ablation period.

WY 2017 winter was characterized by below normal temperatures and precipitation. The Seward airport (PAWD) recorded 42.5% of normal precipitation from October 1st to March 31st. This was reflected in the shallow snowpack measured at the six sites on the northern Harding, the lowest accumulation measurements recorded at the four highest sites and the second lowest accumulation at the two lowest sites in the seven years of the mass balance study.

In addition to the low accumulation recorded at each site it is also notable that this year presented a tighter distribution in the variability of the range of measurements along the elevation gradient. In a typical winter the elevation gradient relates to a temperature gradient where the lowest sites accumulate the least snow and the highest sites accumulate the most snow, and we typically identify ice layers in the snowpack where higher elevation snow events occurred as rain events at lower elevations. Due to the below normal temperatures this winter, all sites remained below freezing throughout most of (the latter two-thirds of) the accumulation period. This was also indicated by the lack of ice layers in the snowpack.

Fall

The Harding Icefield experienced strong winds in September. The Harding Icefield RAWS recorded wind gusts greater than 70 mph on six days in September, maxing out at 121 mph on September 6th. Evidence of these winds was observed at three of the sites; the stakes were severely bent and the plywood was blown off the stake and relocated downslope.

The weather window for flying to the sites for the ablation measurements was established for September 5–September 30. Measurable precipitation was recorded at the Seward Airport on 25 of the 30 days of the month. There was negligible snow at Exit X-ray and no new snow at the other sites.

September 19th was forecasted to be a good day for our flight, but it was a narrow weather window. Temperature and dew point data at the Harding RAWS indicated that there was fog on the Harding icefield near our sites, which was corroborated with the fog that was visible spilling down mountain passes and local peaks around Seward. We waited until late morning when the temperature and dewpoint spread started to increase and fog started to burn off before we agreed to have the pilot fly over our sites on his way to pick us up. There was still a little fog around Exit X-ray and the RAWS, but we were able to begin measurements at the far side of the study area (i.e., the two Glacier A sites), which allowed the fog to burn off and for us to access all sites. Unfortunately, the late start prevented us from measuring Exit Bravo like we usually do during the day of helicopter access. We were able to complete measurements at this site on foot on the same day that we accessed Exit Alpha.

Exit Alpha was not visited during the February stake extension flight. The stake was visible upon arrival during the spring measurement. A pit was dug all the way to the ice. The entire snowpack was sampled with a Norwegian tube. One 3-m section of stake was removed and was left at the site, attached to the stake with a loose noose of duct tape folded over on itself to prevent sticking.

Exit Alpha was visited opportunistically during a personal glacier walk on July 30. One section of stake was removed at that time and left duct taped with the other removed section of stake. H'in = 4.32 m.

The summer ablation site visit occurred on October 3rd. The late season visit was determined by crew availability and a break in heavy rain. However, the work was conducted in rain despite the effort to avoid it.

In previous years, the steam drill had been “slowing down” and required 2.5 hours to drill a hole in 2016. There were no such problems with the steam drill this year. However, the connection between the adaptor for the small canisters and the drill itself seemed loose and twice a build-up of pressure resulted in a mini burst of flame and popping noise after the steam drill was manually moved closer to the hole to allow for maximum drilling depth. This popping has never happened before. Drilling should begin with the drill as close to the hole as possible to avoid this from happening.

All of EX_16_A was removed and EX_17_A was installed above the Index site at the base of the icefall.

Exit Bravo was located during the February stake extension and was extended with an additional 1.5 m stake. Exit Bravo was readily located with over three meters of stake visible above the snow surface during the spring visit. Two sections of stake totaling 4.5 m were removed after the measurement and were loosely duct taped to the stake for reuse in the fall.

Exit Bravo was visited on foot in the fall on October 3, 2017 (see details in Exit Alpha section above). The site was accessed by passing Exit Alpha on the way to the south side of the glacier and staying south while traveling west to avoid the crevasse field up-glacier from Exit Alpha. It's possible that we could have walked directly up the moraine from Exit Alpha to Exit Bravo, but we did not attempt to. If there is more time in the future to scout this out, it may be quicker than walking along the south edge of the ice. Ex_15_B was measured during the fall visit and the top 2 m section of stake was removed. The final 3 m section of stake was well frozen into the ice and should be removed in Fall 18 if possible. EX_17_B was installed at the index site.

Exit Charlie was located during the February visit and was extended by 1.5 m. Approximately 3–3.5 m of snow was at the site in February.

The spring site visit occurred on April 17th. 4 m of stake were removed and duct-taped to the stake for reuse in the fall.

Exit Charlie was the last site visited by helicopter on September 19th. The site was very slushy with a lot of snow algae in the slush and ice worms in the cracks around the site. The plywood from both WY 2016 and WY 2015 were melted out. We did not remove any sections of stake but swapped out the top bent section for a straight one. EX_10_C_6m was visible down-glacier from EX_15_C, but we were unable to remove the top section of stake. There was no new snow nor firn at this site.

EX_14_X was not located during the spring visit at Exit X-ray. A new stake (EX X 17spr 3m) was installed in the Kovacs core hole that remained in the snowpack to crosswalk with the existing stake in the fall. The entire snowpack was measured using the Kovacs corer.

EX_14_X was located in the fall but EX_X_17spr was not; since all WY 17 snow melted at this site, the stake fell over and was covered by the new dusting of snow. We did not have enough time to search for it. EX_14_X was severely bent and the plywood was blown off and was located down-glacier. We replaced a bent stake with a straight one and replaced the plywood around the stake and wrote “SS 2017” (summer surface 2017) on it. There were many crevasses visible around the site, more than I recall seeing at this site in the past. Due to time constraints and crevasses, the index site was not measured with a GPS.

Glacier A Bravo was visited during the February stake extension and was found badly bent, ~50 degrees. The stake was straightened and extended 3.05 m. There were approximately 3–3.5 m of snow at the site during this visit. Glacier A Bravo was located and measured during the spring on April 18th. The entire snowpack was measured using the Norwegian tube and the Kovacs corer.

At the fall site visit, Glacier A Bravo was discovered badly bent and the plywood from the 2016 summer surface was blown off the stake and lying down-glacier of the site (numerous ice worms were found beneath the plywood). Numerous crevasses were visible around the stake.

Glacier A- Charlie was not located during the spring visit on April 18th. The entire snowpack was sampled using a combination of Norwegian tube samples and Kovacs samples. A new stake (GA_C_17spr_3m) was installed to crosswalk with the existing stake in the fall. GA C was visited for ablation measurements on September 19th. Measurements were made based on GA_C_17_Spr and a 1.5 m section was added for the winter. To confirm the firn depth, we dug a pit to 1.58 m where we encountered thick, solid ice. Along the way we encountered an ice lens 0.84 m from the surface and a second ice lens at 1.09 m from the surface.

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