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Glaciological Measurements and Mass Balances from Sperry Glacier, Montana, USA Years 2005-2015

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Abstract

Glacier mass balance measurements help to provide an understanding of the behavior of glaciers and their response to local and regional climate influences. In 2005, the United States Geological Survey established a surface mass balance monitoring program on Sperry Glacier, Montana, USA. This program is the first quantitative study of mass changes of a glacier in this region and continues to the present. This paper describes the methods used during the first eleven years of measurements and reports the associated results. Between years 2005-2015, we estimate Sperry Glacier lost approximately 4.37 m of water equivalent averaged over its entire area. The mean winter, summer, and annual glacier-wide mass balances were 2.92 m per year, -3.41 m per year, and -0.40 m per year respectively. We derive these cumulative and mean results from an expansive dataset of snow depth, snow density, and ablation measurements taken at selected points on the glacier, the resultant mass balance point values for these measurement sites, and a time series of seasonal and annual glacier-wide mass balances for all eleven measurement years. We also provide measurements of total glacier surface and accumulation areas for select years. All data have been submitted to the World Glacier Monitoring Service and are available at http://dx.doi.org/10.5904/wgms-fog-2016-08. This foundational data enhances our basic understanding of mass balance of Sperry Glacier, and future work will focus on the processes that control accumulation and ablation patterns across the glacier.

1. Introduction

The worldwide retreat of glaciers in the past century is seen as both an effect of, and evidence for, global climate change. In the United States (U.S.), one example of this global trend is the retreat of glaciers in Glacier National Park (GNP), which is located in the Rocky Mountains of northwest Montana (Fig. 1). In 1850, during a period known as the Little Ice Age, approximately 150 glaciers existed in the area now encompassed by GNP, making it one of the largest concentrations of glaciers in the U.S. Rocky Mountains (Key et al., 2002 & Pedersen et al., 2004). The amount of glacier-covered area has receded dramatically since that time, a trend documented by decades of photographs and measurements of glacier area (Alden, 1914 & 1923; Dyson, 1948; Johnson, 1980; Carrara and McGimsey, 1981, 1988, Carrara, 1989; Key et

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al., 2002). By 1998, 37 named glaciers remained, 11 of these had a total surface area of 8.25 km^2, a 67% loss compared with 25.5 km^2 for the same 11 glaciers in 1850 (Key et al, 2002). The fraction of glacier area lost since 1900 is markedly higher in GNP than in the other mountain regions of the contiguous U.S. (Fountain, 2007).

This trend and its effects are expected to continue. One geospatial model scenario predicts a complete disappearance of five glaciers in GNP by 2030 with continued warming (Hall and Fagre, 2003). Another process-based model that specifically examines Sperry Glacier suggests the glacier may last until about 2080 given the current climate and glaciological conditions (Brown et al., 2010). The retreat of glaciers in GNP has had and will continue to have hydrologic and ecological effects in the region's mountain ecosystems and some degree of economic effect for its human communities (Clark et al., 2015).

It is widely accepted that the regional retreat of glaciers has been driven by climate change, at least some of which is anthropogenic (IPCC, 2013). However, no quantitative measurements of mass changes have ever been conducted for any glacier in GNP. Without such studies, it is difficult to determine whether or how the retreat of GNP's glaciers directly reflects regional climate trends. To address this gap, the U.S. Geological Survey (USGS) established a long-term mass balance monitoring program in which glaciological, surface area, and hypsometric measurements provide a quantitative estimate of mass changes for one glacier in the park, Sperry Glacier. The changes and trends measured on this glacier serve as a reference for others in the region, an approach outlined by Fountain et al (1997) and since adopted widely (Kaser et al, 2003). Sperry Glacier is now one of four benchmark glaciers studied by the USGS Glaciers and Climate Program, with two benchmark glaciers located in Alaska, and one in Washington.

This paper presents the data collection methods and results from the first eleven years of measurements, from 2005-2015. Results include measurements of glacier area, ice motion, snow depth, snow density, and ablation of snow, firn, and ice. We calculate the associated point balance values (Cogley et al., 2011) for the snow depth and ablation measurement sites. We also compute and report conventional glacier-wide seasonal and annual mass balances (Cogley et al., 2011) for the same period. Results from this work will improve our understanding of glacier responses to climate in GNP as well as the role of glaciers as a water resource. The data

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sets included in this paper may also be used for general analysis of regional and global glacier mass balance trends.

1.1. Sperry Glacier Site Description

Sperry Glacier (48.623° N, -113.758° W) is a small cirque glacier located immediately west of the Continental Divide and roughly in the geographic center of GNP (Fig. 1). The remote location limits the type and manner of research that can be undertaken at the site. Sperry Glacier is located in a backcountry zone managed as de facto wilderness by the U.S. National Park Service. Helicopter access to the glacier is very limited due to environmental and cultural concerns as well as management policies. Therefore, with very few exceptions, all equipment and instruments must be backpacked to the glacier, which requires a 15 km hike or ski with over 1500 m of elevation gain.

Sperry was chosen as a site for surface mass balance measurements because of two factors that are rare in the region. First, it has a history of previous scientific studies that documents its progressive retreat over the past century (Johnson, 1980). Second, its physical characteristics best meet those recommended for detailed mass balance studies and regional benchmark glacier status (Fountain et al. 1997; Kaser et al. 2003). These characteristics include a well-defined drainage basin and topographic features that are representative of many of Glacier Park's glaciers.

Sperry is a winter-accumulation type glacier composed of temperate ice. It is located within the Flathead River watershed, in the headwaters of the Columbia River basin. It lies in a north-facing cirque and is roughly fan-shaped and wider than it is long relative to the flow direction, which is predominantly north-northeast (Fig. 2). The irregular terminus measures about 1200 m across and steep rock walls rising another 100-300 m above the glacier line its east and most of its west flanks. In 2005, it had a median elevation of 2450 m, and an altitude range of 2250 m to 2800 m. Numerous small streams drain its broad terminus, making it impractical to measure runoff with a single stream gage

The local climate is influenced by both maritime and continental air masses because of the study area's position along the Continental Divide. However, given its position on the western and predominantly windward side of the Divide, Pacific storm systems dominate the

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weather. These bring heavy precipitation and moderate temperatures as warm, moist Pacific fronts collide with and lift over the Rocky Mountains.

2. Methods

2.1. Glacier Geometry and Accumulation Area Mapping

Initially, the surface area of Sperry was mapped using aerial photographs taken in September, 1998. To ensure that mass balance calculations included the most current estimates of the glacier surface, we mapped the terminus using multi-channel GPS receivers at the end of the 2003, 2005, 2007, 2009, and 2013 ablation seasons. We conducted the mapping by walking the terminus (Fig. 2) of the glacier, with the terminus defined as any ice contiguous with the main body even if debris-covered. We did not map the glacier margin below the near-vertical cirque walls that rise above the upper elevation margins of the glacier for safety reasons.

We differentially-corrected the GPS data collected during the mapping, then smoothed the track by removing obvious errors such as loops caused by the mapper's movement. We overlaid each mapped terminus with a polygon of the 1998 glacier outline and calculated the area of each resulting polygon for each year. For these years, the resulting values should be considered the maximum possible glacier extent for a given year because they do not include any small changes at the glacier margins below the steep cirque walls or on the ridge above the headwall. In 2015 the complete glacier margin was mapped again from 0.5 meter resolution aerial imagery and included area changes across the entire glacier including the margins along the flanks and head of the glacier.

During years 2005, 2009, 2010, and 2013 we walked the seasonal snow line with a GPS unit at the end of the ablation season. This end-of-summer snow line separates the ablation and accumulation areas on the glacier since the area at elevations above this line were still covered with snow that accumulated the previous winter. We divided these mapped accumulation areas by the total area of the glacier to obtain the accumulation area ratio (AAR).

Area altitude distributions (AAD) were calculated for eight years of the eleven year study period (Table 1) from a time series of 5 m resolution digital elevation models (DEM). These DEMs were derived from aerial photographs taken of the glacier in August or September so as to capture the glacier near its mass minimum (Fahey, 2014). The raw DEM coverage reached

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beyond the glacier's margin so each DEM was clipped by the most recently measured glacier margin so that all cells in the DEM represent snow/firn/ice-covered area within the glacier margin. Each cell from these glacier DEMs was then binned into 50 m bands and then summed to derive the total area for each elevation band.

2.2. Study Assumptions and Conventions

For this study, we determined conventional (Cogley et al., 2011) seasonal and annual surface mass balances for Sperry Glacier using the glaciological method combined with the most recently mapped glacier margin and AAD. We followed established protocols for measuring snow depth, sampling snow density, and installing and reading ablation stakes (Ostrem and Brugman, 1992; Kaser et al 2003). The snow depth measurements included all snow deposited on the glacier surface during the winter season, including seasonal snowfall, avalanche debris, and wind-transported snow. Because we were not able to directly measure melt that occurred during the winter season, we did not specifically account for it in the winter balance terms of mass balance calculations. Similarly, we did not include summer-season precipitation in our summer balance terms because it fell primarily as rain and was assumed to run off and not measurably contribute to the glacier's mass change. In addition, local climate data (Finklin, 1986) show that both winter-season melt and summer-season precipitation likely have minimal contributions to the net balances of each period. Because Sperry Glacier is a small, temperate glacier, we assumed that runoff transported nearly all melt off the glacier with negligible mass retained by refreezing and/or the formation of superimposed ice. This is a common assumption (Kaser et al 2003) and is supported by our field observations.

We determined the mass balance year for field measurements and balance calculations using a time system that combined stratigraphic and floating-date systems (Cogley et al 2011). Ideally, measurements of accumulation are conducted when the glacier's mass is at its maximum for the year and ablation measurements during its minimum, with the balance year the period between two consecutive minima. For Sperry, such timing is impractical because difficulties with access preclude continuous monitoring. Also the time of the maxima and minima can vary by several weeks between years.

We therefore defined each mass balance year as the period between the latest ablation stake readings in successive summer seasons (Table 2). These readings were timed to occur as late as possible in September or early October of each calendar year, so as to coincide as closely as possible with the formation of that year's end of summer surface, which represents the minimum annual mass for that year. We used the previous summer's surface as the reference surface for snow depth probing at the end of the subsequent accumulation season, and defined winter balances b_w (winter point balances) and B_w (winter glacier-wide balances) as the net mass gain between formation of the previous year's summer surface and the subsequent year's peak accumulation. We defined summer balances b_s (summer point balances) and B_s (summer glacier-wide balances) as the net mass loss between the peak accumulation, approximated by the earliest date in the spring when depth measurements and ablation stake installations occurred, and the formation of that year's end of summer surface. Under these definitions, the winter season at Sperry Glacier typically runs from mid-September/early-October to late-May/late-June, with the summer season comprising the remaining part of the year (Table 2). The balance year is thus roughly equivalent to the hydrologic year.

We adhered to the notation and signing conventions delineated in Cogley et al (2011) and used terms as defined in that glossary. The dimensions of the depth and surface altitude measurements are length (m). Multiplying these by the sampled snow density or, for firn and ice, an assumed density of 720 and 874 kg m^{-3} respectively, yields a mass per unit area whose units are kg m^{-2} of water equivalent. Because mass balance is a rate of mass change, its dimensions are mass per unit time (M T^{-1}), though as is common in mass balance studies, we report mass primarily in length (m) of water equivalent (w.e.) because it allows for ease of visualization and we omit the time dimension as our measurements span roughly one year (Cogley et al 2011). Thus all balances are reported in meters of water equivalent (m w.e.) for each year in the 11 year study period.

2.3. Mass Balance Point Measurements (b_w, b_s, b_a)

A winter mass balance point measurement (b_w) is the sum of accumulation and to a much lesser extent, ablation over the winter season. It represents nearly all the annual mass input at any point that accumulates continuously as precipitation and as wind and avalanche

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deposited snow. To obtain b_w we combined snow depth measurements taken at locations on the glacier with a snow density value.

A summer mass balance point measurement (b_s) represents the sum of ablation, and to a much lesser extent, any accumulation over the summer season. To obtain b_s we measured the height loss on ablation stakes that were drilled into the glacier's surface (Supplement) at the start of the ablation season.

An annual mass balance point measurement (b_a) represents the sum of accumulation and ablation over the mass balance year. These were calculated by summing the winter balance (b_w) and summer balance (b_s) values measured at each ablation stake site (Supplement) for each respective year.

2.3.1. Snow Depth and Density Measurements

The primary method for taking snow depth measurements was to probe vertically through the seasonal snowpack to the previous summer surface. A sectional solid aluminum probe was used and depths were measured to the nearest 0.01 m or 0.05 m depending on the year. Measurement locations were recorded using handheld GPS receivers. Depending on the GPS equipment available, some locations were differentially corrected. For safety reasons, we made no measurements on the steep headwall above the bergschrund (Fig. 2).

In 2005, density measurements were made in two snow pits (Supplement). The first pit was located roughly 275 m above the terminus; the second pit was 500m further up the glacier, roughly 125m below the bergschrund. During 2006, 2007, and 2008 measurements were made at one pit dug at the lower location. From 2009-2013 no density measurements were made on the glacier and a bulk density value derived from the relationship between snow depth and density using the 2005-2008 data was employed to calculate balances. Density measurements resumed in 2014 were taken at ablation stake sites A, C, and D that year, and at sites A and D in 2015.

For the years 2005-2008, direct density measurements were made by weighing samples of snow from the shaded face of a snow pit. The samples were collected in 10 cm increments with a 1000 cm^3 cutter and weighed on a digital scale. Snow pits were dug to the previous summer's surface in 2005 and 2006 when the snow depth was less than 4.75m. During 2007

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and 2008 when the height of snow was greater than 5 m, the snow was sampled only in the upper 2.0-3.5 m portion of the column.

In 2014 and 2015 density was measured by weighing snow samples collected at 3 or 4 specific depths in a 1.5 m deep snow pit. One sample was taken within 0.10 m of the snow surface, the second at about 1.0 m and the third at about 1.5 m. At depths greater than 1.5 m from the snow surface, snow samples were obtained using a coring cylinder at 0.10 to 0.30 m intervals until the previous summer's surface was reached. Densities were then derived by weighing these samples.

2.3.2. Ablation Measurements

We measured the surface change at the ablation stake locations and obtained a water equivalent length value for the total ablation by multiplying the height loss of snow, firn, and ice by their respective densities. We used the same density value for the snow component of b_s as used to calculate b_w at that point. We used previously published estimates of the densities of firn and ice to account for mass loss of those components (Cuffey and Paterson, 2010). We used a value of 720 kg m^{-3} for firn, which equals the mean between the approximate maximum densities of snow (600 kg m^{-3}) and firn (840 kg m^{-3}). For ice melt on the glacier's surface we used a density of 874 kg m^{-3}, the mean value for glacier ice as described by Cuffey and Paterson's (2010).

2.4. Glacier-Wide Mass Balances (B_w, B_s, B_a)

Glacier-wide mass balances represent the mean balance for the infinite number of possible points across the glacier's surface. These values cannot be directly measured and are typically estimated from point measurements or interpolations of point measurements. We estimate glacier-wide mass balances for the winter (B_w) and summer (B_s) seasons as well as an annual balance representing the entire mass balance year (B_a). We used the site-index method where one or more point balances in a specific elevation band represent the average balance across the entire surface area for that elevation band. Balances in each respective band were multiplied by the band's area yielding a volume. Volumes from each band were summed, then this quantity was divided by the glacier's total surface area to provide the specific glacier-wide

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mass balance value. The number and size of the elevation bands varied slightly between years depending on the point balances available and the changing geometry of the glacier. In the case where more than one point balance was located within a band, we use the mean value.

During some years no measurement points were located at the very lowest elevations of the glacier below 2300 m. In these cases, measurement points within 10 m of 2300 m were used to assign balances to this elevation band. In situations where this was not possible, then a single point balance, taken from the lowest elevation measurement point(s) was used instead (Supplement). For some balance years there were no measurements taken at the higher elevations of the glacier between 2550-2650 m (Supplement). The winter and summer balances for these bands were derived using a gradient found between two point balances and their respective elevations at two different measurement sites. The stakes used to calculate these gradients are presented in the data tables included in our Supplement. Furthermore, no measurements of any kind have been collected at the uppermost elevations of the glacier on the steep southern headwall above 2650 m. With respect to the winter balance, observations show that frequent avalanches prevent large amounts of snow from accumulating on this steep slope (Fig. 2). Thus it is likely winter balances will be lower on areas above the bergschrund than those immediately below it. For the area located on this headwall, we used the mean winter point balance taken from all measurement points on the glacier to represent winter balances. Ultimately the snow depths on the headwall are unknown, yet it is necessary to assign balances to this region. Using the mean b_w is a method to accomplish this while minimizing the influence of these uncertain balances on B_w. For the summer balances on the headwall we again used a gradient value derived from an ablation versus elevation relationship observed at two different stake sites (Supplement).

Annual balances for elevation bands with no point balances were derived by summing the winter and summer values assigned to them via the extrapolation methods discussed above. This sometimes resulted in negative balances on the steep southern headwall. This is consistent with observations showing much of this headwall will melt down to firn and ice during years with a strongly negative B_a despite the fact this is the highest elevation region of the glacier (Fig. 2).

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2.5. Cumulative Mass Balance

The cumulative mass balance is the total mass gained or lost over multiple balance years. For this study, we calculated cumulative mass balances for the eleven study years by summing the glacier-wide annual (B_a) balances.

3. Results and Discussion

3.1.1. Glacier Mapping – Terminus Position and Glacier Area

Sperry Glacier has decreased by 0.08 km^2 in total area since 2005 at an average rate of 0.007 km^2 a^{-1} (Fig 3, Table 3). Overall the terminus continually retreated with each measurement interval. However there are selected, small areas where the terminus has slightly advanced. The largest changes occurred around the glacier's northernmost edges, where the elevation of the glacier is lowest. At this location, many small fingers of ice melted away or separated from the main ice body and islands of bedrock began to appear (Fig. 4). Some of the change/error in area for each period is likely attributable to changes in personnel conducting the mapping. For certain regions, especially where rock debris conceals and/or distorts the terminus location, different personnel have interpreted the margin's location slightly differently. The existence and annual variability of rock covered ice makes distinguishing ice compared to rock somewhat difficult.

3.1.2. Glacier Mapping - Accumulation Area

In years 2005, 2009, 2010, and 2013 the accumulation area ratios were 34%, 46%, 48%, and 36% respectively. The average value is 41%. While we did not measure the AAR for any other year, we noted that during the two years with the most positive B_a (2008 and 2011), most of the glacier's surface was still covered with snow from previous winter at the end of the ablation season in late September/early October.

3.2. Mass Balance Point Measurements (b_w, b_s, b_a)

When combining all points from all years (n=477), the mean b_w was 2.64 m w.e. with a standard deviation of 0.88 m w.e. The minimum was 0.00 (due to wind-scouring down to bare ice) and the maximum was 5.66 m w.e. The mean values for all points binned by individual year

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had a narrower range of 1.92 m w.e. and a lower standard deviation of 0.54 m w.e. Snow depth and density plus winter balance values for all measurement points are presented in the tables included in the Supplement. Table 4 details summary statistics for the winter point balances.

A somewhat complicated relationship exists between winter balance and elevation after averaging the b_w values from all years within their respective 50 m elevation bands (Fig. 5). On the lowest elevation portions of the glacier, between the terminus and about 2400 m, the 11-year averaged winter balances increased gradually with rising elevations. On the middle of the glacier, the winter balances actually decreased slightly with elevation. On the upper elevations, winter balances increased rapidly as elevation increases.

In 2005, 2006, and 2007 the number and locations of ablation stakes varied. Beginning in 2008, when seven stakes were placed in the same locations each year, the winter, summer, and annual balances were measured consistently at each site every year with the exception of one stake in 2009. Stake Z was added in 2015 to better measure the uppermost accumulation zone and to compare balances found at nearby stake D.

Ablation, as reflected in the change of the glacier surface elevation at the ablation stake sites, followed a similar temporal pattern in all ten years. The surface change was greatest during June and July and sometimes early August with surface lowering rates ranging between -0.06 to -0.10 m d^{-1} and a mean rate of -0.08 m d^{-1}. From mid-August until the end of the ablation season in September or October, surface lowering rates dropped consistently among all years and range from -0.01 to -0.05 m d^{-1} with an average rate of -0.03 m d^{-1}. The decrease in late summer ablation rates is due to multiple factors. When the glacier's surface at the stake sites transitions from snow to ice, surface lowering rates decline due to the higher density of ice. In addition the shorter days with lower sun angles of late summer/early fall combined with the cooler, cloudier, and wetter weather all act to slow ablation. Finally, August and early September storms will often deposit small amounts of new snow on the glacier which slows or temporarily halts ablation.

When combining all stake measurements from all years (n=74), the mean stake b_s was -3.57 m w.e., with a range of 3.06 m w.e. and a standard deviation of 0.70 m w.e. The stake means for each year had a narrower range of 2.37 m w.e. and a standard deviation of 0.64 m

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w.e (Table 5). However, less variance existed within individual years. The range of b_s amongst stakes for individual years spanned 0.51 to 1.58 m w.e. and the standard deviations ranged from 0.20-0.51 m w.e.

The relationship between summer balance and elevation varied between years and sometimes in a complex manner. When all b_s values from all years were grouped within 50 m elevation bands and averaged, b_s did not consistently increase with increasing elevation (Fig. 6).

When combining the annual point balances from all stakes from 2005-2015 (n=80), the 11-year mean stake b_a was -0.70 m w.e., with a range of 5.53 m w.e. and a standard deviation of 1.18 m w.e. The mean b_a for each year varied between -1.55 m w.e. to 2.41 m w.e. (Table 6). The range amongst all measurement points for individual years was lower as well and spanned 1.08 to 3.52 m w.e. with standard deviations falling between 0.38-1.14 m w.e.

3.3. Glacier-Wide Mass Balances

3.3.1. Winter Mass Balances (B_w)

The site index method resulted in B_w values ranging from 2.19 m w.e. in 2007 to 4.13 m w.e. in 2011 with a mean of 2.92 m w.e for 2005-2015 (Table 7). For the first five years, B_w never exceeded 2.78 m w.e. But from 2010-2014 winter accumulation values consistently added more mass to the glacier, with B_w exceeding 3.00 m in 2011, 2012, and 2014. In 2015 the winter balance dipped below the 11-year average with a value of 2.79 m.

B_w contour maps reveal a sometimes complicated relationship between winter mass balance and elevation (Supplement). For all years except 2005, 2012, and 2015, the mid-elevations between 2400-2500 m had winter balance values that were less than those found at lower elevations (Fig. 7). For instance, during years 2007-2010 and 2013, 2014 winter balance values at these mid-elevations were the lowest for any elevation band on the glacier. Winter balances increased rapidly with elevation above 2500 m until the bergschrund located at the base of the cirque wall at about 2650 m. On the headwall above the bergschrund winter balances decrease because of assumed mass re-distribution on the slopes below, likely through avalanches and wind transport.

3.3.2. Summer Mass Balances (B_s)

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B_s values ranged from -4.31 m w.e. in 2013 to -2.11 m w.e. in 2008 with a mean for the 11-year record of -3.41 m w.e (Table 7). The summers of 2013 and 2015 were exceptional for ablation and were the only two years where B_s was lower than -4.00 m w.e. 2008 and 2010 saw the least amount of summer ablation and B_s did not drop below 3.00 m w.e. For all other years B_s values ranged between -3.93 and -3.17 m w.e.

Similar to the winter balances, summer mass balances did not always vary consistently with elevation (Fig. 8). For years 2005, 2006, 2008, and 2010 B_s continually increased, although sometimes very slightly, with increasing elevation. For the remaining years the smallest summer balance values were often found closer to the mid-elevations of the glacier, usually between 2350 and 2400 m. Some general trends are revealed when the summer balances for each elevation band were averaged for the period of record. Mean summer balances vary only by a few cm w.e between the terminus and 2500 m, an area encompassing most of the glacier. Above 2500 m summer balances increase at a fairly consistent rate of about 0.25 m w.e. per 50 m elevation gain (Fig. 8).

3.3.3. Annual Mass Balances (B_a)

The first three balance years, 2005-07, were strongly negative with 2007 having the lowest B_a on record at -1.52 m w.e. In 2008, conditions reversed and the glacier experienced its most strongly positive year with a B_a of 0.97 m w.e. 2009 was the second most negative year at -1.39 m w.e. and then in 2010 the annual balance was near neutral with a value of 0.15 m w.e. The annual balance in 2011 was the second most positive at 0.83 m w.e. and the balance in 2012 was slightly positive as well at 0.41 m w.e. The three years of neutral or positive annual balances ended in 2013 with value of -1.07. Annual balance in 2014 was neutral (0.07 m w.e.) and finally the annual balance in 2015 was the third most negative year on record (-1.22 m w.e.). The mean site index B_a for the study period is -0.40 m w.e (Table 7).

Again, similar to the winter and summer balances, the changes in annual balances with elevation were variable (Fig. 9) and (Supplement). For years 2005, 2006, 2010, and 2012 B_a continually increased, although at different rates, with increasing elevation from the terminus to the bergschrund at 2650 m. However, for the seven remaining individual balance years, the lowest annual balances were found at the mid-elevations between 2400 and 2500 m. The

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annual balance values on the headwall above the bergschrund are reduced, with negative values in 2005, 2007, and 2009. It is important to note again that balances on this section of the glacier come with high uncertainty because they are not measured directly. However, observations revealed some years where the headwall is composed mostly of ice and would thus have negative balances, while the slopes immediately below it are still covered in the previous winter's snow and would have maintained a positive balance.

3.4. Cumulative Mass Balances

Cumulatively the glacier lost 4.37 m w.e. between 2005 and 2015 by way of the site index method. About 70% of that loss occurred during the first three years of the study. Both seasonal and annual balances exhibited more variability in the remaining eight years of the study.

Cumulative balances in the ablation zone, which typically comprises about 60% of the glacier ranged from -11.28 to -9.79 m w.e. Meanwhile in the accumulation zone, cumulative balances were as low as 3.38 m w.e. and as high as 21.94 m w.e. in the region directly beneath the headwall. These differences translate to cumulative balances that change as much as 30.00 m w.e. over less than 400 m of linear distance and fewer than 200 m of elevation gain.

4. Conclusions

Conventional glacier-wide seasonal and annual mass balances were estimated using glaciological methods from 2005-2015 at Sperry Glacier and reported along with all the accompanying glaciological measurements. Measurements of glacier extent were also measured during certain years and are included in this paper.

Results from the site index method reveal that, on average, Sperry Glacier loses about 0.40 m w.e each year. During the 11-year study period, glacier-wide winter balances ranged from 2.19 m w.e. to 4.13 m w.e., glacier-wide summer balances between -4.31 and -2.11 m w.e., and annual glacier-wide balances between -1.52 and 0.97 m w.e. The mean winter and summer glacier-wide mass balances were 2.92 m w.e. and -3.41 m w.e. respectively.

Point balances ranged even wider. Some winter point balances exceeded 5.00 m w.e., while at other locations on the same day there were patches of bare ice where no winter snow had accumulated. During particularly hot and long summers, summer point balances approached -5.00 m w.e. at certain locations.

Between 2005 and 2015, it is estimated Sperry Glacier lost between 4.37 m w.e. averaged over its entire area. In the ablation zone (which averaged about 60% of the glacier area for the four years it was measured) cumulative balances were as low -11.28 m. In the accumulation zone, cumulative balances ranged from as little as 3.38 all the way up to 21.94 m w.e. on the region directly beneath the headwall.

The variable relationship between mass balance and altitude on Sperry is likely affected by concurrent multiple drivers that are not yet fully understood. Further research is needed to improve our knowledge of the processes that control accumulation and ablation patterns on this glacier. Specific to ablation, local factors that regulate the balance of heat energy input from solar radiation such as aspect, slope angle, and cirque-wall shading, combined with the type of material present on the glacier's surface may have greater influence on ablation rates than the gradient between altitude and air temperatures. The winter balance is likely bolstered by the snow added to the glacier from avalanches and wind, especially in the areas directly beneath the cirque walls, but this re-distribution of mass remains to be quantified.

Sperry's surface area has decreased by 0.08 km^2 over the 2005-2015 time period, a change of about 9%. Most of this decrease occurred in the northeastern section, the lowest elevation area of the glacier.

The timing, number, and distribution of measurements taken on the glacier varied considerably among years. A developing understanding of the accumulation and ablation patterns over this time has been used to guide the current methods used for data collection. Now measurements are taken at fewer points that are more strategically located. No doubt future work will continue to influence the type, number, location, and timing of measurements taken on the glacier.

Acknowledgements

This research was supported by the U.S. Geological Survey's Climate and Land Use Change Research and Development Program. Help with fieldwork was provided by a large group of field technicians and volunteers over the years. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Alden, W.C.: Glaciers of Glacier National Park, U.S. Dept. of the Interior, Washington D.C., 48 pp., 1914.

Alden, W.C.: Rate of movement in glaciers of Glacier National Park, Science, 57(1470), 268, 1923.

Brown, J., Harper J., and Humphrey, N.: Cirque glacier sensitivity to 21st century warming: Sperry Glacier, Rocky Mountains, USA, Global Planet. Change, 74(2010) 91-98, doi.org/10.1016/j.gloplacha.2010.09.001, 2010.

Carrara, P.E.: Late quaternary glacial and vegetative history of the Glacier National Park region, Montana, U.S. Geol. Surv. Bulletin 1902, U.S. Dept. of the Interior, Washington D.C., 64 pp, 1989.

Carrara, P. E., and McGimsey, R. G.: The late-neoglacial histories of the Agassiz and Jackson Glaciers, Glacier National Park, Montana, Arctic Alpine Res., 13(2), 183-196, 1981.

Carrara, P.E. and McGimsey, R.G.: Map showing distribution of moraines and extent of glaciers from the mid-nineteenth century to 1979 in the Mount Jackson area, Glacier National Park, Montana, U.S. Geol. Surv. Miscellaneous Investigations Series, U.S. Dept. of the Interior, Washington D.C. 1988.

Clark, A. M., Harper, J. T., Fagre, D. B., 2015: Glacier-Derived August Runoff in Northwest Montana. Arctic, Antarctic, and Alpine Research, 47(1): 1-16. doi.org/10.1657/AAAR0014-033, 2015.

Cogley, J.G., Hock, R., Rasmussen L.A., Arendt, A.A., Bauder, A., Braithwaite, R.J., Jansson, P., Kaser, G., Moller, M., Nicholson, L., and Zemp, M.: Glossary of Mass Balance and Related Terms. IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris. 2011.

Cuffey, K.M. and Paterson, W.S.B.: The Physics of Glaciers 4th Ed., Elsevier, Burlington MA, USA and Oxford, UK., 2010.

Dyson, J. L.: Shrinkage of Sperry and Grinnell Glaciers, Glacier National Park, Montana. Geogr. Rev., 38(1), 95-103, 1948.

Fahey, M.: National Civil Applications Program, U.S. Geol. Surv., Reston, VA, USA, 2014.

Finklin, A. I.: A Climatic Handbook for Glacier National Park: With Data for Waterton Lakes National Park, U.S. Forest Service Intermountain Research Station, Ogden, UT., 1986.

Fountain A.G., Krimmel, R.M., and Trabant, D.C.: A strategy for monitoring glaciers, U.S. Geol. Surv. Circular 1132, U.S. Government Printing Office, Washington D.C., 1997.

Fountain, A. G.: A century of glacier change in the American West, EOS Trans. of the American Geophysical Union, 88(5), 2007.

Hall, M. H. P., and Fagre, D. B.: Modeled climate-induced glacier change in Glacier National Park, 1850-2100, BioScience, 53(2), 131-140, 2003.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324. 2013.

Johnson, A.: Grinnell and Sperry Glaciers, Glacier National Park, Montana: a record of vanishing ice, U.S. Government Printing Office, Washington D.C., 1980.

Kaser, G., Fountain, A., Jansson, P., Heucke, E., and Knaus, M.: A manual for monitoring the mass balance of mountain glaciers: UNESCO, 137 pp, 2003.

Key, C. H., Fagre, D. B., and Menicke, R. K.: Satellite image atlas of glaciers of the world, glaciers of North America - Glaciers of the western United States, J365-J381, U.S. Government Printing Office, Washington D.C., 2002.

Pederson, G.T., Fagre, D.B., Gray, T., and Graumlich, L.J.: Decadal-scale climate drivers for glacial dynamics in Glacier National Park, Montana, USA, Geophys. Res. Lett. 31, L12202. doi:10.1029/2004GL019770, 2004.

Ostrem, G. and Brugman, M.: Glacier Mass Balance Measurements: A Manual for Field and Office Work. Ministry of Supply and Services – Env. Canada and Norwegian Water and Energy Admin., 224 pp., 1991.

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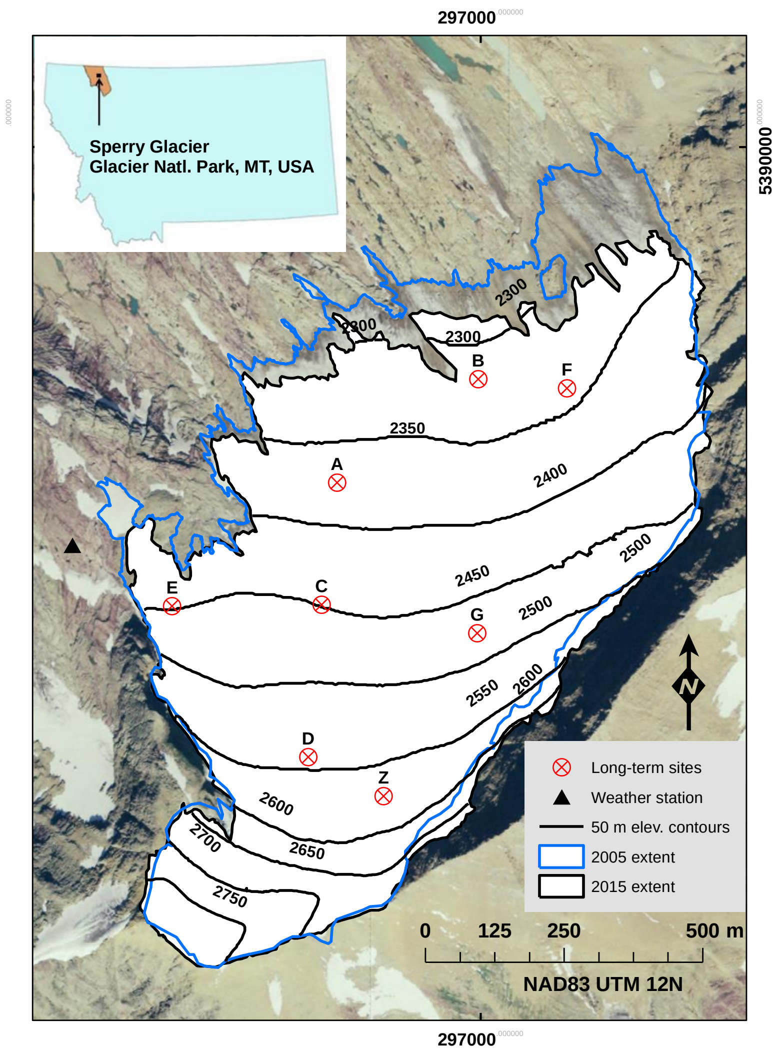

Figure 1. An overview map of Sperry Glacier which displays the locations of the long-term measurement sites and the weather station, plus changes in glacier extent between 2005 and 2015. Glacier surface elevations are contoured from a DEM derived from imagery pairs taken on September 2nd, 2005. The aerial photo in this figure was taken on August 26th, 2005 by the U.S. National Agricultural Imagery Program.

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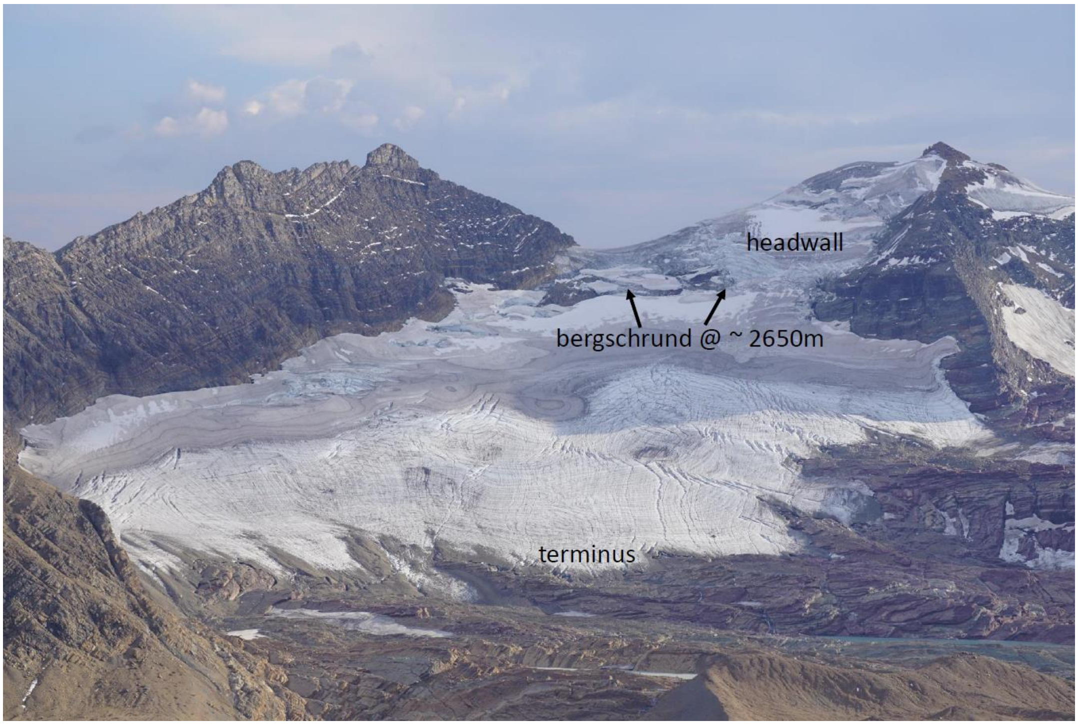

Figure 2. Oblique photo showing overview of the glacier, the bergschrund, and headwall.

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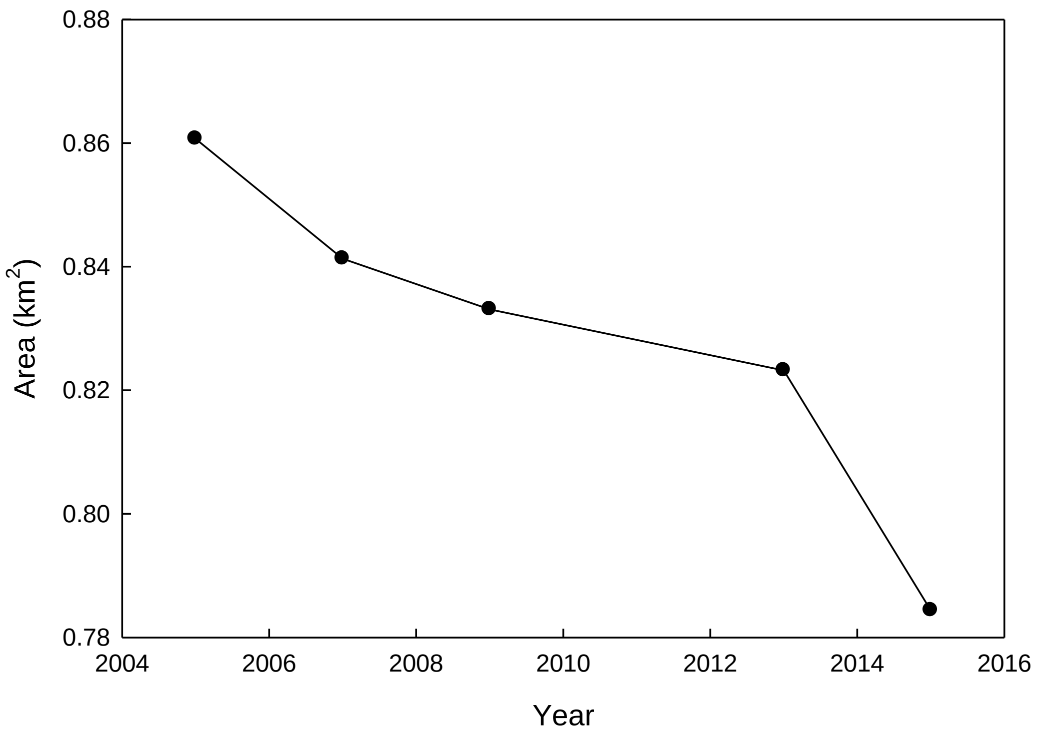

Figure 3. Measured extent for Sperry Glacier for the period 2005-2015.

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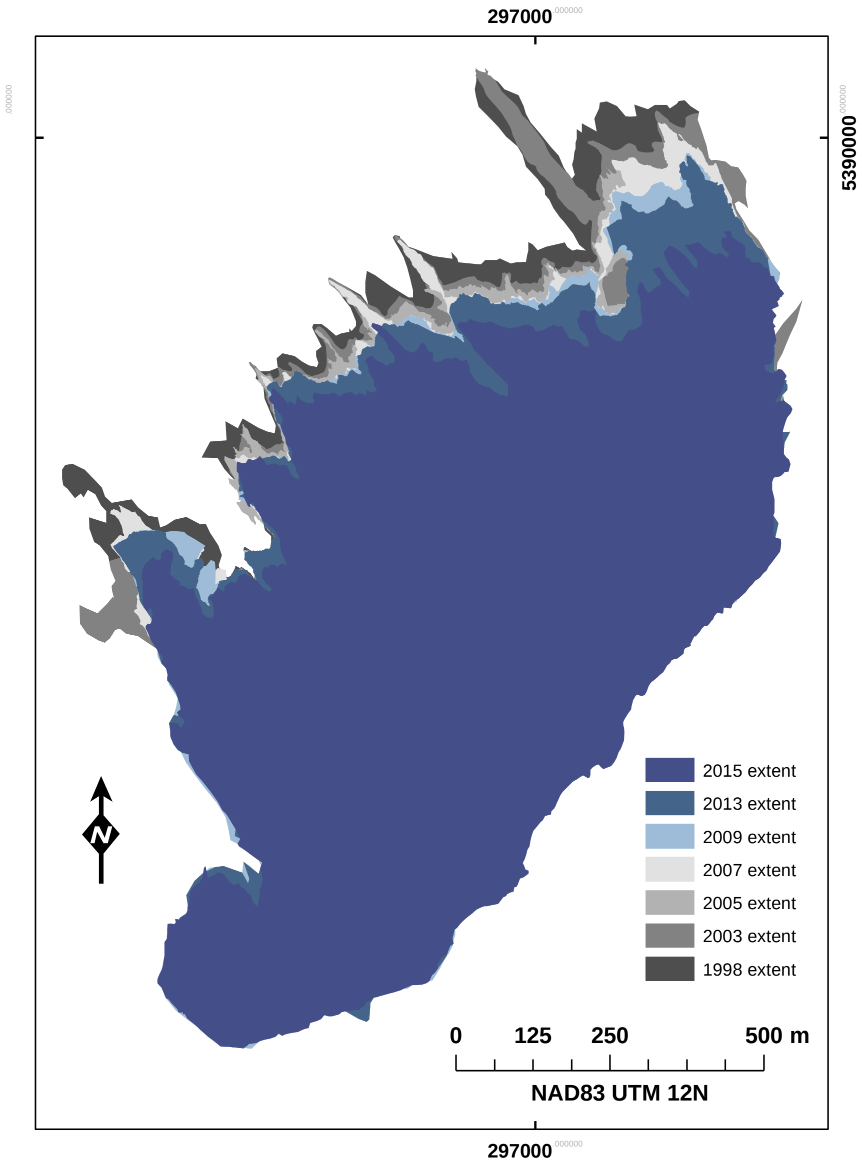

Figure 4. Mapped outlines of Sperry Glacier for the period 1998-2015.

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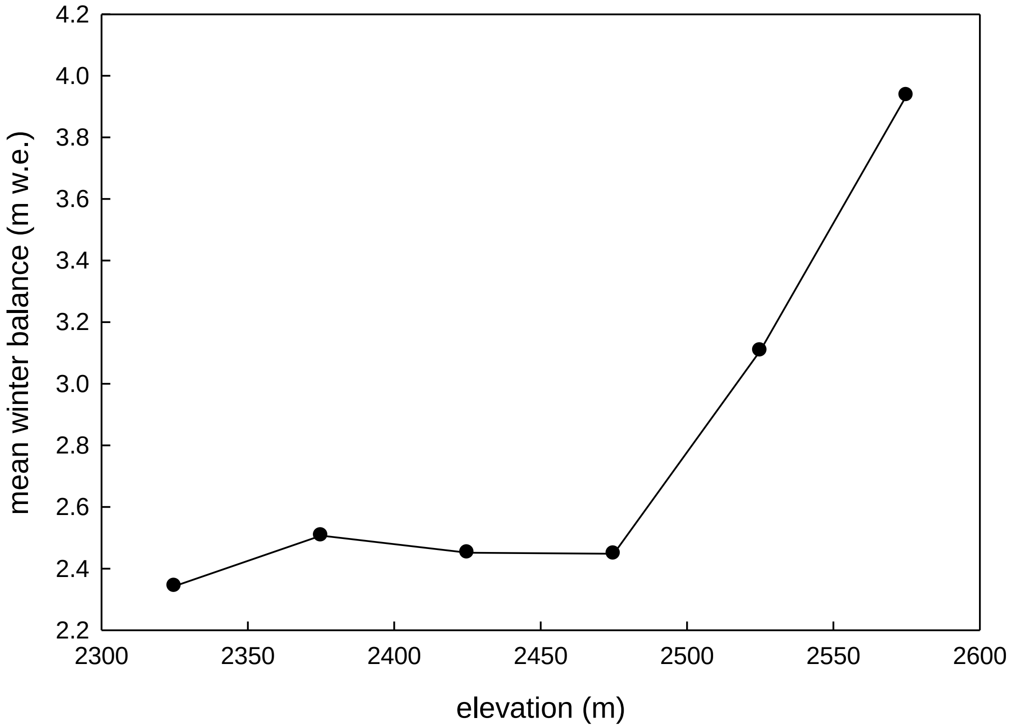

Figure 5. Winter balance measurements from all points/all years which were grouped by elevation (NAD83) into 50 m bins. We plotted the mean for each bin against the mean elevation for each bin. The number of measurements in each bin varies within years and among years depending on the year's measurements.

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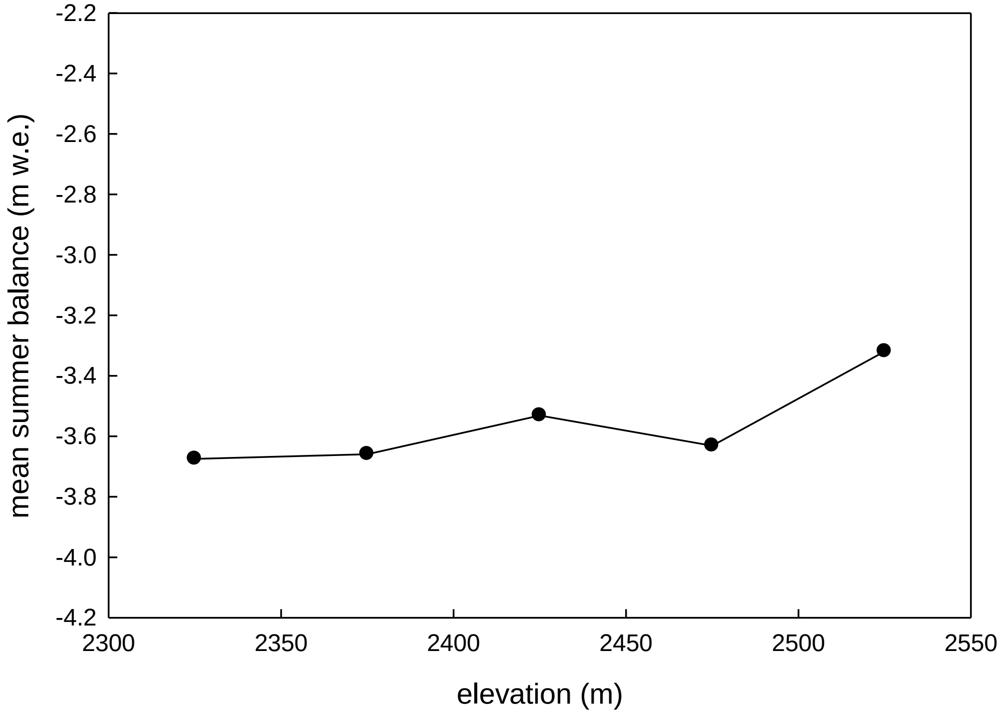

Figure 6. Summer balance measurements from all points and all years which were grouped by elevation (NAD83) into 50 m bins. We plotted the mean for each bin against the mean elevation for each bin. The number of measurements in each bin varies within years and among years depending on the year's measurements. Note scale is equal to that in Figure 5.

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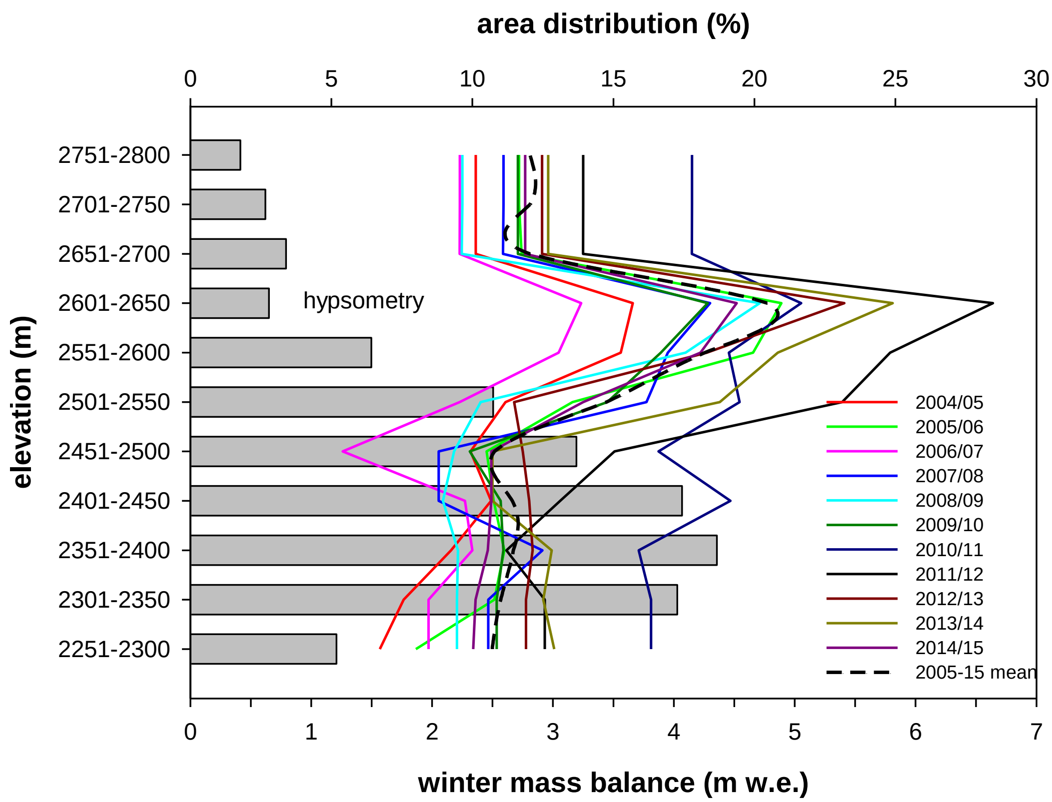

Figure 7. Winter mass balances for years 2005-2015 plotted against each elevation (NAD83) band. Area altitude distribution is from 2005. Gray bars represent the percentage of glacier area within each elevation band. Colored lines plot the winter mass balances across the elevation range of the glacier.

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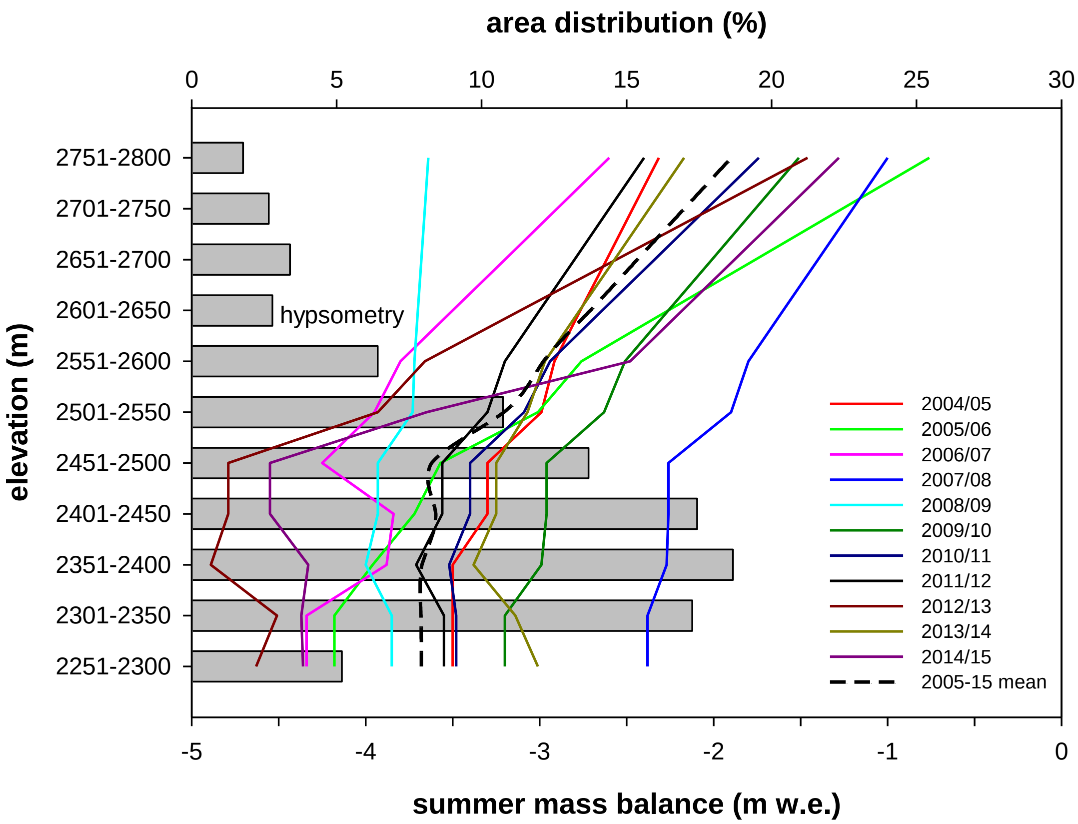

Figure 8. Summer mass balances for years 2005-2015 plotted against each elevation (NAD83) band. Area altitude distribution is from 2005. Gray bars represent the percentage of glacier area within each elevation band. Colored lines plot the summer mass balances across the elevation range of the glacier.

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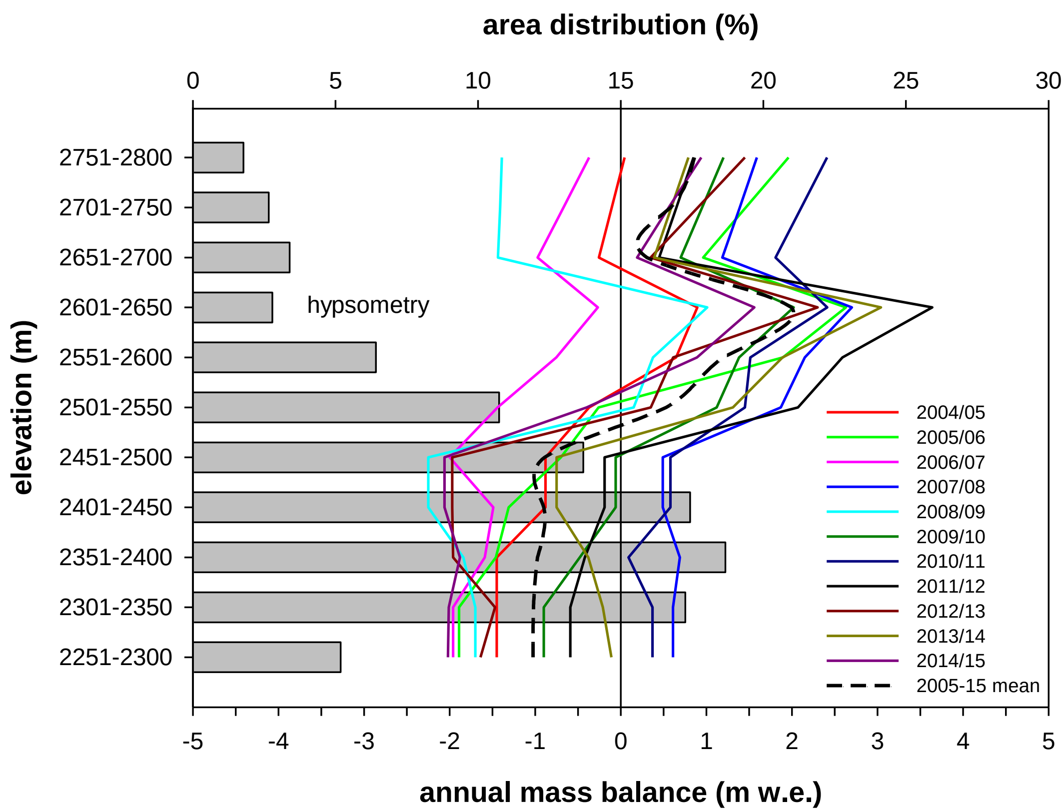

Figure 9. Annual mass balances for years 2005-2015 plotted against each elevation (NAD83) band. Area altitude distribution is from 2005. Gray bars represent the percentage of glacier area within each elevation band. Colored lines plot the annual mass balances across the elevation range of the glacier.

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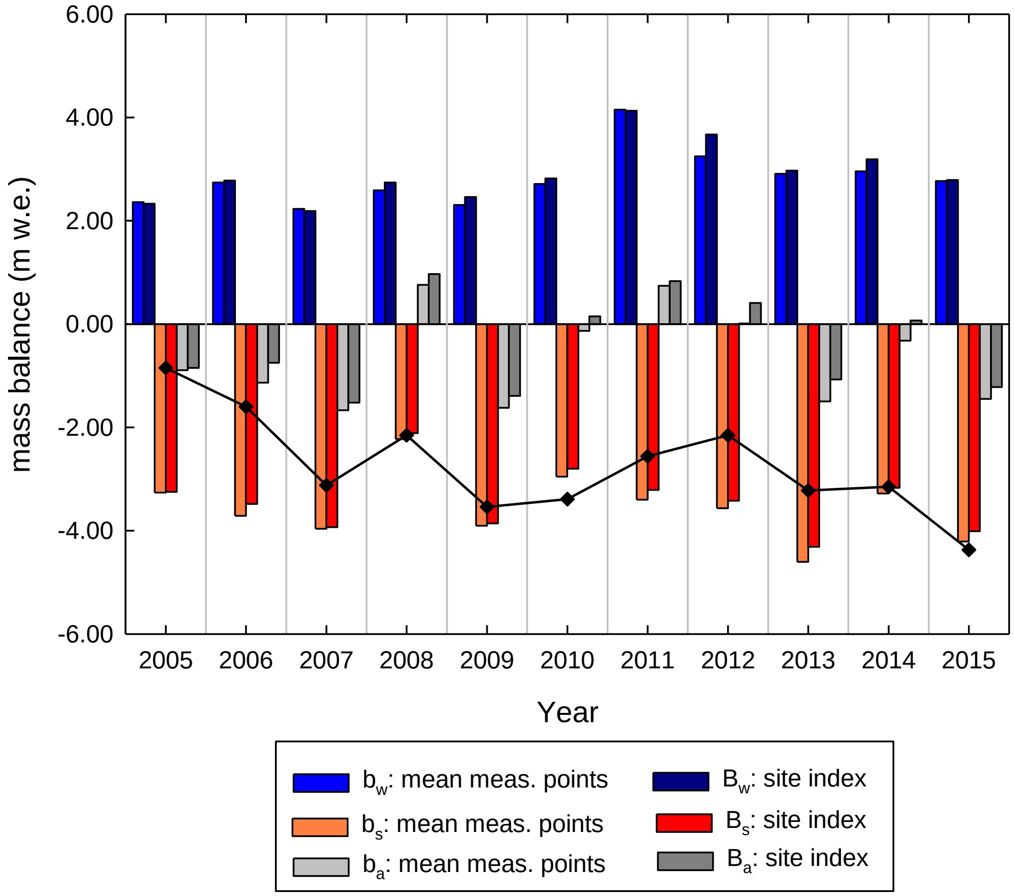

Figure 10. Bars represent the seasonal and annual mass balances on the glacier. The black line depicts the running cumulative balance for the period of record.

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Table 1. List of acquisition dates for aerial photographs and measured terminus positions used to derive each DEM and AAD.

AAD Year	DEM Date	Glacier Margin Meas. Date
2005	9/2/2005	9/9/2005
2006	9/2/2005	9/9/2005
2007	8/25/2007	9/8/2007
2008	9/11/2008	9/8/2007
2009	8/28/2009	8/26/2009
2010	8/28/2009	8/26/2009
2011	8/10/2011	8/26/2009
2012	8/10/2012	8/26/2009
2013	8/21/2013	9/4/2013
2014	9/7/2014	9/4/2013
2015	9/7/2014	9/25/2015

Table 2. Dates for mass balance years and winter and summer seasons for the study years, 2005 through 2015.

Mass Balance (mb) Year	Start mb Year/ Winter Season	End Winter Season/Start Summer Season	End Summer Season/mb Year	# Days Winter Season	# Days Summer Season	# Days mb Year
2005	Unknown	23-Jun-05	9-Sep-05	Unknown	78	Unknown
2006	9-Sep-05	8-Jun-06	28-Sep-06	272	112	384
2007	28-Sep-06	26-May-07	9-Sep-07	240	106	346
2008	9-Sep-07	16-Jun-08	12-Sep-08	281	88	369
2009	12-Sep-08	16-Jun-09	18-Sep-09	277	94	371
2010	18-Sep-09	23-Jun-10	2-Oct-10	278	101	379
2011	2-Oct-10	24-Jun-11	3-Oct-11	265	101	366
2012	3-Oct-11	28-Jun-12	1-Oct-12	269	95	364
2013	1-Oct-12	11-Jun-13	27-Sep-13	253	108	361
2014	27-Sep-13	11-Jun-14	18-Sep-14	257	99	356
2015	18-Sep-14	25-May-15	22-Sep-15	249	120	369
mean	21-Sep	13-Jun	21-Sep	264	100	367
min	9-Sep	25-May	9-Sep	240	78	346
max	3-Oct	28-Jun	3-Oct	281	120	384

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Table 3: Sperry Glacier areal extent, 2005-2015

Year	Measurement date	Measured Area (km^2)	Δ area (km^2)	Rate Δ/years; (km^2)	% Change	Rate (% change/ years)
2005	9-Sep	0.86	0.00	0.000	0.0	0.0
2007	8-Sep	0.84	-0.02	-0.010	-2.3	-1.2
2009	26-Aug	0.83	-0.01	-0.004	-1.0	-0.5
2013	4-Sep	0.82	-0.01	-0.002	-1.2	-0.3
2015	25-Sep	0.78	-0.04	-0.022	-5.5	-2.8

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Table 4. Summary statistics for 2005-20105 winter point balances

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Mean	St Dev	Min	Max	Range
End Winter/Start Summer	23-Jun	8-Jun	26-May	16-Jun	16-Jun	23-Jun	24-Jun	28-Jun	11-Jun	11-Jun	25-May	13-Jun	11	25-May	28-Jun	34
# Measurements	82	110	40	12	96	71	27	19	21	7	8	45	38	7	110	103
Mean	2.36	2.72	2.23	2.59	2.31	2.71	4.15	3.25	2.91	2.96	2.76	2.81	0.54	2.23	4.15	1.92
Median	2.10	2.58	2.30	2.85	2.13	2.66	4.09	3.05	2.92	2.83	2.51	2.73	0.55	2.10	4.09	1.99
Standard Deviation	0.83	0.86	0.64	0.95	0.91	0.70	0.57	0.98	0.53	0.71	0.70	0.76	0.15	0.53	0.98	0.45
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	3.41	1.81	2.20	2.04	1.99	1.04	1.26	0.00	3.41	3.41
Maximum	4.12	5.66	3.81	3.77	5.05	4.12	5.10	5.42	4.28	4.38	4.22	4.54	0.65	3.77	5.66	1.89
Range	4.12	5.66	3.81	3.77	5.05	4.12	1.70	3.61	2.07	2.34	2.23	3.50	1.28	1.70	5.66	3.97

Table 5. Summary statistics for 2005-2015 summer point balances.

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Mean	StDev	Min	Max	Range
End Summer	9-Sep	28-Sep	9-Sep	12-Sep	18-Sep	2-Oct	3-Oct	1-Oct	27-Sep	18-Sep	22-Sep	21-Sep	9.122400003	9-Sep	3-Oct	24
# Stakes	3	8	7	7	6	7	7	7	7	7	8	7	1	3	8	5
Mean	-3.26	-3.71	-3.96	-2.23	-3.90	-2.95	-3.40	-3.56	-4.60	-3.28	-4.21	-3.55	0.64	-4.60	-2.23	2.37
Median	-3.30	-3.89	-4.08	-2.32	-3.82	-3.02	-3.32	-3.55	-4.63	-3.22	-4.35	-3.59	0.65	-4.63	-2.32	2.31
Standard Deviation	0.25	0.41	0.32	0.20	0.25	0.22	0.22	0.23	0.38	0.21	0.51	0.29	0.10	0.20	0.51	0.31
Minimum	-3.50	-4.18	-4.34	-2.43	-4.23	-3.20	-3.76	-3.88	-4.96	-3.51	-4.91	-3.90	0.74	-4.96	-2.43	2.53
Maximum	-2.99	-3.01	-3.43	-1.90	-3.63	-2.63	-3.09	-3.26	-3.93	-3.04	-3.33	-3.11	0.53	-3.93	-1.90	2.03
Range	0.51	1.17	0.91	0.52	0.61	0.56	0.67	0.62	1.03	0.48	1.58	0.79	0.35	0.48	1.58	1.10

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Table 6. Summary statistics for 2005-2015 annual point balances.

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Mean	StDev	Min	Max	Range
End Balance Year	9-Sep	28-Sep	9-Sep	12-Sep	18-Sep	2-Oct	3-Oct	1-Oct	27-Sep	18-Sep	22-Sep	21-Sep	9	9-Sep	3-Oct	24
# Stakes	5	8	11	7	6	7	7	7	7	7	8	7	1	5	11	6
Mean	-0.89	-1.13	-1.67	0.76	-1.62	-0.13	0.74	0.01	-1.50	-0.32	-1.45	-0.65	0.91	-1.67	0.76	2.43
Median	-0.88	-1.14	-1.79	0.81	-1.84	-0.12	0.37	0.06	-1.64	-0.37	-1.94	-0.77	0.98	-1.94	0.81	2.74
Standard Deviation	0.38	0.57	0.55	0.68	0.90	0.68	1.02	1.13	0.88	0.86	1.14	0.80	0.25	0.38	1.14	0.76
Minimum	-1.45	-1.89	-2.32	-0.32	-2.40	-0.90	0.00	-1.33	-2.35	-1.48	-2.63	-1.55	0.87	-2.63	0.00	2.63
Maximum	-0.37	-0.26	-0.65	1.87	0.15	1.12	2.90	2.07	0.35	1.33	0.89	0.85	1.13	-0.65	2.90	3.55
Range	1.08	1.63	1.67	2.19	2.55	2.02	2.90	3.40	2.70	2.81	3.52	2.41	0.76	1.08	3.52	2.44

Table 7: Glacier-wide balances. Units are m w.e. for all values.

Year		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Mean - All Years	St. Dev. - All Years
Winter balance	b_w: mean meas points	2.36	2.74	2.23	2.59	2.31	2.71	4.15	3.25	2.91	2.96	2.77	2.82	0.54
	B_w: site index	2.33	2.78	2.19	2.74	2.46	2.82	4.13	3.67	2.97	3.19	2.79	2.92	0.57
Summer balance	b_s: mean stakes	-3.26	-3.71	-3.96	-2.23	-3.90	-2.95	-3.40	-3.56	-4.60	-3.28	-4.21	-3.55	0.64
	B_s: site index	-3.25	-3.48	-3.93	-2.11	-3.86	-2.80	-3.21	-3.42	-4.31	-3.17	-4.01	-3.41	0.62
Annual balance	b_a: mean stakes	-0.89	-1.13	-1.67	0.76	-1.62	-0.13	0.74	0.01	-1.50	-0.32	-1.45	-0.65	0.91
	B_a: site index	-0.85	-0.75	-1.52	0.97	-1.39	0.15	0.83	0.41	-1.07	0.07	-1.22	-0.40	0.91
Cumulative: site index		-0.85	-1.60	-3.12	-2.15	-3.54	-3.39	-2.56	-2.15	-3.22	-3.15	-4.37		