Mass balance of a cirque glacier in the U.S. Rocky Mountains

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Glacier National Park, Montana, USA, contains 27 cirque glaciers, most less than 1 km^2 and together comprising about 17 km^2. These glaciers lie at relatively low elevation (2000 – 3000 m a.s.l.) and latitude (48° N) and have undergone dramatic retreat since the mid-nineteenth century, when an estimated 150 glaciers existed. Continuing volume losses and the disappearance of glaciers in recent decades are used as key indicators of regional warming. Here we present initial results from a long-term study initiated in 2005 on Sperry Glacier (48.6° N, 113.75° W), a 0.8 km^2 cirque glacier that has undergone an 80% reduction in size since the mid 1800s. We calculated seasonal and annual balances using the direct glaciological method augmented with data from an automated weather station adjacent to the glacier and data from a nearby automated snow pillow. The net annual balance averaged -1.0 m w. eq. for the 2005 and 2006 balance years. Specific balances showed significant transverse spatial variability due to site-specific processes that augment accumulation or mute ablation. These processes have a significant effect on the mass balance of the glacier. Proxy measures showed that the 2005 and 2006 balance years likely had very low accumulation or very high ablation, respectively, relative to other years in recent decades.

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 U.S., the most commonly cited example of this global trend is the retreat of glaciers in Glacier National Park (GNP), which is located in the northern Rocky Mountains in Montana. The loss of glacier area in the region is greater than in other mountain areas in the contiguous U.S. (Fountain, 2007), and one model predicts a complete disappearance of glaciers in GNP by 2030 with continued warming (Hall and Fagre, 2003). Despite the attention, there have been no quantitative studies of the changes in mass or volume of the glaciers in GNP. It is therefore difficult to determine how directly the dramatic changes in glacier area reflect climate trends in this region. To address this issue, we initiated a long-term study of the mass balance of Sperry Glacier, a remnant cirque glacier in GNP. The objectives of this study are to provide quantitative data regarding mass and volume changes on the glacier over time, distinguish climatic and other processes that influence its mass balance, and add to the mass balance record for the Rocky Mountains of the U.S. and Canada. This presentation presents the study's results to date.

2. Study Site

In 1850, roughly 150 glaciers existed in the area now encompassed by GNP, making it one of two significant concentrations of glaciers in the US Rocky Mountains. These glaciers were primarily products of the Little Ice Age (LIA) and have receded dramatically since that time (Carrara, 1989). By 1998, only 27 glaciers remained; 11 of these glaciers had a total surface area of 8.25km^2, a 67% loss compared with 25.5km^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). It is widely accepted that the regional retreat of glaciers has been driven by climate change, at least some of which is anthropogenic, and one model predicts a complete disappearance of glaciers in GNP by 2030 with continued warming (Hall and Fagre, 2003).

Because of its position astride the Continental Divide, the climate in GNP is influenced by both maritime and continental air masses. Temperature and precipitation patterns are marked by strong altitudinal gradients. Mean temperatures for July, which is generally the warmest month, are nearly twice as warm in valley locations (about 1500m a.s.l.) as they are for mountain sites (2500m a.s.l.). Similarly, annual precipitation averages 584 mm on the western and eastern edges of the park, but over 2500 mm at higher elevations in the center of the park (Finklin, 1986). Snowpacks in the GNP region are strongly influenced by multi-decadal climate patterns (McCabe and Dettinger, 2002; Selkowitz et al, 2002), but exhibit no significant trends since 1922 (Selkowitz, 2002). The snowpack at 2000m typically peaks about May 1 each year, but can vary by up to four weeks earlier or later.

Sperry Glacier (48.6^o N, 113.75^o W) was chosen as a site for long-term mass balance monitoring because of its history of previous research and physical characteristics. Sperry Glacier was first photographed in 1894 and mapped in 1901, and the first scientific descriptions and measurements of it were published in the early 20th century (Alden, 1914; Alden, 1923). Dyson (1948) documented the glacier's dramatic retreat and thickness changes in the first half of the 20th century. In the mid-20th century, the National Park Service and U.S. Geological Survey conducted more or less annual studies of the glacier; though mass balance measurements were not part of these studies, they did include installation of ablation stakes, measurements of surface velocity and thickness change, and plane-table mapping that resulted in several 1:4800 and 1:6000 scale maps of the glacier surface and environs (Johnson, 1980). Later researchers mapped and dated the moraines fronting Sperry Glacier and outlined the post-Pleistocene glacial history of GNP (Carrara and McGimsey, 1981; Carrara and McGimsey, 1988; Carrara, 1989). The most recent study documented the progression of glacier retreat throughout GNP over the past century using satellite imagery and aerial photos (Key et al, 2002). This history of previous research is relatively unique in the region; only three other glaciers in GNP – Grinnell, Blackfoot/Jackson, and Agassiz - have been similarly documented.

Sperry glacier's physical characteristics make it better suited for mass balance studies than the other well-studied glaciers in GNP. The glacier is not broken by rock or ice cliffs nor has it fragmented into several smaller ice masses, and it does not calve into a pro-glacial lake; the glaciers named above each have one or more of these characteristics. With an area of 0.86 km^2 (2005) Sperry Glacier is slightly smaller than those glaciers yet still one of the larger glaciers remaining in GNP. Its median elevation of 2450 m a.s.l. makes Sperry one of the higher glaciers in the region. These characteristics suggest it is still sensitive to temperature and precipitation fluctuations, and thus appropriate for mass balance studies.

However, Sperry Glacier is remote and lies within a National Park, two facts which can influence how and what research is conducted there. Accessing the glacier requires a 12.5 km hike or ski with nearly 1800 m elevation gain. Helicopter access to the glacier is extremely limited due to environmental concerns and park management policies, requiring nearly all equipment and instruments to be carried to the study site. Other glaciers in the area are as or more remote, and the management restrictions apply to all glaciers, so access issues cannot be avoided by changing the study site.

Sperry Glacier, like most glaciers in GNP, retreated most rapidly in the first half of the 20th century (Carrara, 1989). In 1913 Sperry Glacier still covered 3.41 km^2, roughly 88% of its LIA maximum in the mid-nineteenth century (Carrara and McGimsey, 1988). In the next decade, retreat accelerated, and the glacier fragmented into one main ice mass and two smaller ice masses. The main ice body occupied 1.99 km^2 in 1927, and lost area at a mean annual rate of 0.026 km^2 a^{-1} through 1946. The rate of retreat then halved over the next three decades to 0.013 km^2 a^{-1} (Carrara and McGimsey, 1988). Between 1979 and 2005, the rate nearly halved again, so that by 2005, the main ice body of Sperry Glacier occupied 0.86km^2 while the two stagnant fragments had mostly disappeared.

The loss of glacier area was accompanied by significant down-wasting of the glacier surface. Dyson (1948) estimated that the mean elevation loss near the 1946 glacier terminus was over 90 m since 1913; from a comparison of plane-table maps of the glacier surface in 1938 and 1946 he calculated a mean annual height loss of almost 3 meters for the lower half of the glacier. Johnson (1980) estimated the glacier surface lowered over 45 m on its eastern edge between 1913 and 1944; for the period 1949-69, he reported pronounced thinning up to 35 m near the terminus of the glacier but a slight thickening of the upper elevation parts of the glacier. This thickening may have been due to the anomalously high snowpacks that marked much of the period (CITATION-Selkowitz et al, 2002).

3. Methods

For 2005 and 2006 balance years, we measured the surface mass balance using the standard glaciological method (Ostrem and Brugman, 1992). Winter balance (B_w) measurements were made in June, shortly after the snowpack peak, by probing to the previous summer surface. For the 2005 balance year, 74 measurements were made in five transects with measurements spaced 25 or 50 m apart. The primary transect followed the longitudinal profile of the glacier's main direction of flow from the bergschrund to the terminus; the remaining transects roughly paralleled the edges of the glacier. For the 2006 balance year, 95 measurements were made in six transects. We repeated three transects from 2005, including the primary longitudinal transect, then made three equally spaced transverse transects across the main body of the glacier to capture snow depths where the 2005 measurements suggested snow depths were most variable. Depth measurements both years took several days to complete; all measurements were normalized to the earliest date using the mean change in snow depth measured at identical or adjacent points on different dates.

The snow density was sampled every 10 cm in the shaded wall of snowpits using a 1000cc sampler and weighed on a digital scale. In 2005, density measurements were made in two snowpits dug 3.15 and 4.45 m to the previous summer surface near the top and bottom of the longitudinal depth profile. In 20006, measurements were made at in a 4.5m deep snowpit at the lower of the two sites from the previous year. The sampled values were binned by taking the mean of the five measurements for each 50 cm interval, then developing a snow depth/ density relationship by fitting a logarithmic curve to the mean density for the entire snow column at each 50 cm step. For 2005 we fit the curve to the mean of the sampled values for both snowpits.

We measured ablation at ablation stakes set into the glacier surface using a portable steam drill. Most stakes were set after the snow depth measurements were made, but those set later were normalized to the earliest date using mean change in snow height at other stakes. Intermediate measurements were made roughly every month during the ablation season before the final measurements were made in September immediately after the first snowfall. Five stakes were measured for the 2005 balance year, three along the primary longitudinal transect and two in a transverse transect in roughly the middle of the glacier. For the 2006 balance year, ten stakes were used, four in the same positions as 2005 and the remainder distributed across the glacier surface. The height change measurements were converted to mass change by multiplying by the snow density calculated from the balance year's logarithmic depth- density relationship or the mean density for firn (715 kg m^{-3}) or glacier ice (874 kg m^{-3}) taken from Paterson (1994).

To calculate seasonal and annual net balance (B_n), we interpolated the point depth and ablation measurements across the glacier surface using Surfer (Golden Software, 2002). Snow depth was interpolated with a kriging algorithm and 10 x 10 m grid cells. Snow water equivalent (SWE) for each cell was calculated by applying the balance year's logarithmic depth-density relationship to each interpolated depth value; the result was B_w. The summer balance (B_s) was calculated by interpolating the point mass change measurements from each ablation stake across the glacier surface using the same kriging algorithm and cell size. Subtracting the B_s grid from the B_w grid gave B_n for each balance year.

We next developed proxies for accumulation and ablation that would allow a comparison of the two years of measurements with annual values for recent decades. Previous studies have shown that SWE measurements at various snow courses and automated snow pillows in the GNP region have similar inter-annual variations; we assumed that measurements at Flattop SNOTEL, the snow pillow closest to Sperry Glacier, would closely represent the variability in SWE at the glacier. However, a comparison of the two years of measurements at the glacier with the same years peak SWE at Flattop showed that actual SWE at the glacier was much greater. We therefore normalized the annual peak SWE at Flattop to 2006, giving us a relative proxy for winter accumulation at the glacier for the 1970-2006 period of record for SWE measurements at Flattop SNOTEL.

Temperature data from an automated weather station (AWS) installed adjacent to the glacier in 2006 allowed us to statistically correlate temperatures between that station and Flattop. We then calculated the total positive degree days (PDD) at Flattop for 1985-2006 and normalized that to 2006. The total PDD at Flattop served as a relative proxy for summer conditions driving ablation at the glacier.

4. Results

The point snow depth, density and ablation measurements for the two balance years are summarized in Table 1. For the 2005 balance year, we calculated B_w to be 2.19 m w. eq., B_s as -3.41 m w. eq. and B_n as -1.22 m w. eq. For the 2006 balance year, the values were 3.12, -3.99 and -0.87 m w. eq. The accumulation/ ablation area ratio (AAAR) was 0.09 for 2005 and 0.31 for 2006.

The interpolated snow depths, ablation and specific balance values showed significant transverse spatial variability for both balance years (Figure 1). For cells at similar elevations, spatial variability was greatest near the mean elevation of the glacier, where specific balances spanned over 4 m w. eq. At other elevations on the glacier, the range was typically 1.5 to 2.5 m w. eq.

The accumulation proxy showed that most years (63%) had lower snow accumulation than 2006, with 2005 accumulation among the lowest in the 1970-2006 period. The ablation proxy showed 887 and 1221 PDD for 2005 and 2006 respectively. More than half the years had lower total PDD than 2005, but only one year had a lower total than 2006.

Table 1: Sperry Glacier snow depth, density and ablation, balance years 2005 and 2006

Balance Year	Snow depth measurements: normalized date, elevation range & mean (m a.s.l)	Measured snow depth range, mean & standard deviation	Mean density, depth/ density relationship, r^2	Ablation measurements: Measurement dates, elevation range & mean (m a.s.l)	Measured ablation range, mean, & standard deviation (m w. eq.)
2005	175; 2287-2593; 2422	0-7+ m; 4.09 m; 1.3 m	563 kg m^{-3}; ρ=14.5ln(depth)+541.5; 0.99	176-252; 2362-2525; 2450	2.97-3.54; 3.26; 0.2
2006	160; 2298-2582; 2428	0-9+ m; 4.63 m; 1.46 m	594 kg m^{-3}; ρ=53.8ln(depth)+523.8; 0.933	178-271; 2362-2525; 2437	2.95-3.70; 3.46; 0.25

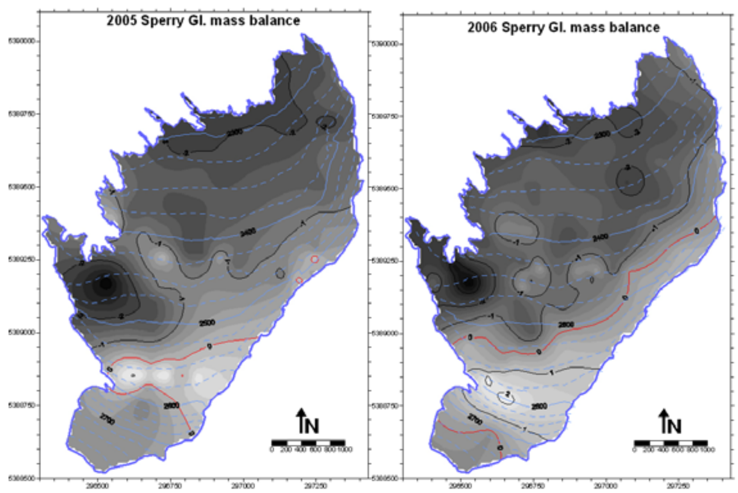

Figure 1: Maps showing elevation contours and specific balances for Sperry Glacier, balance years 2005 and 2006.

5. Discussion

We have not included uncertainties or error estimates with the calculated B_w, B_s, and B_n values for the two balance years because we have not yet systematically assessed measurement errors. However, Jansson (1999) analyzed the sensitivity of mass balance calculations to different factors such as sampling schemes, snow probing errors, and snow density models, and concluded they have small effects - generally on the order of +- 0.1 m w. eq. - on mass balance determinations. Similarly, Fountain and Vecchia (1999) showed that the number of stakes needed for mass balance determinations on small glaciers is scale invariant and that five to ten stakes provided reasonable estimates. Because we used measurement methods very similar to those used for other glaciers and installed five to ten stakes, we expect the uncertainties on our mass balance determinations to be of the same order as those for similar studies.

We compared the patterns of specific balance apparent on the maps for both balance years to photographs of the glacier to determine if the interpolated values were artifacts of the interpolation algorithm or represented the variability of accumulation and ablation. The comparison showed that many of the mapped patterns echoed patterns evident on the photographs. The locations of the mapped features were very similar, though the magnitudes were not identical. We concluded that the mapped spatial variability was representative of actual conditions.

We attribute the spatial variability in specific balance to site-specific processes that redistribute mass or enhance or mute ablation. Among the former are wind and avalanches, while the latter include shading and wind-driven turbulent flux variations. These topographically controlled processes complicate the relationship between elevation and specific balance that dominates mass balance for most glaciers (Paterson, 1994; Fountain and Vecchia, 1999). The accumulation areas for both balance years was limited to sites immediately below the cirque headwall where avalanche- and wind-deposited snow enhanced climatically derived accumulation and shading conserved snow and ice by minimizing ablation. Previous studies have described how similar processes can dominate mass balance on very small glaciers (Kuhn, 1995), and these very small glaciers are often seen as insensitive to climatic temperature and precipitation (Hoffman et al, 2007; Fountain, 2007). At Sperry Glacier, however, they appear to have a significant but not overwhelming effect on the glacier's mass balance.

This study's initial results suggest partitioning climatic and topographic influences on the mass balance of Sperry Glacier is necessary to fully assess how directly the glacier's mass balance reflects climate trends in this region. The study provides the first quantitative measurements of mass changes in the glaciers of GNP and ads to the limited mass balance records available for the U.S. Rocky Mountains. This effort is part of a wider attempt to establish long-term monitoring of mass balance at glaciers in western U.S.

6. References

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