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Re-analysis of Alaskan Benchmark Glacier Mass-Balance Data Using the Index Method

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U.S. Department of the Interior
U.S. Geological Survey

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By Ashley E. Van Beusekom, Shad R. O’Neel, Rod S. March, Louis C. Sass, and Leif H. Cox

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Conversion Factors and Datum

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
	Pressure	
kilopascal (kPa)	0.009869	atmosphere, standard (atm)
kilopascal (kPa)	0.01	bar
kilopascal (kPa)	0.2961	inch of mercury at 60°F (in Hg)
kilopascal (kPa)	20.88	pound per square foot (lb/ft^2)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)
	Energy	
joule (J)	0.0000002	kilowatthour (kWh)

Conversion Factors and Datum—Continued

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Datum

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

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Re-analysis of Alaskan Benchmark Glacier Mass-Balance Data Using the Index Method

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Abstract

At Gulkana and Wolverine Glaciers, designated the Alaskan benchmark glaciers, we re-analyzed and re-computed the mass balance time series from 1966 to 2009 to accomplish our goal of making more robust time series. Each glacier’s data record was analyzed with the same methods. For surface processes, we estimated missing information with an improved degree-day model. Degree-day models predict ablation from the sum of daily mean temperatures and an empirical degree-day factor. We modernized the traditional degree-day model and derived new degree-day factors in an effort to match the balance time series more closely. We estimated missing yearly-site data with a new balance gradient method. These efforts showed that an additional step needed to be taken at Wolverine Glacier to adjust for non-representative index sites.

As with the previously calculated mass balances, the re-analyzed balances showed a continuing trend of mass loss. We noted that the time series, and thus our estimate of the cumulative mass loss over the period of record, was very sensitive to the data input, and suggest the need to add data-collection sites and modernize our weather stations.

Introduction

Glaciers respond to changes in climate with changes in length and thickness (for example, Meier, 1962; Dyurgerov and Meier, 2000). Thus, the time-series of geometric change provides insight into glacier-climate interactions in both the past and the present. Resolving the relationship between surface forcing (climate) and changes in the geometry of a glacier is accomplished through mass-balance estimates, which involve measuring the change in glacier mass at specific sites and extrapolating those changes over the glacier surface for specified time intervals (for example, Hooke, 2005).

As part of a large-scale effort to monitor glacier changes, the U.S. Geological Survey (USGS) has maintained a long-term mass-balance program at three North American glaciers. These so called ‘Benchmark Glaciers’ include South Cascade Glacier, Washington; and Gulkana and Wolverine Glaciers in Alaska (fig. 1). Measurements began at South Cascade Glacier in 1957 and at the Alaska glaciers in 1966; the data collected in this program form the longest continuous set of glacier mass-balance data in North America (Josberger and others, 2007, 2009). These glaciers were selected because of simple logistics, locations in different climatic regimes, and small size. They represent the three primary climatic regimes in the United States that support the existence of glaciers.

Wolverine Glacier (fig. 1) in the coastal mountains of south-central Alaska’s Kenai Peninsula experiences a maritime climate with high precipitation rates. This south-facing glacier spans over 1,000 m in elevation and reaches 1,680 m at its head. In 2009, it is approximately 7 km long with an areal extent of 17 km^2 in its 24.5 km^2 basin. Mass turnover rates are high. The seasonal mass balance amplitude is about 2.5 meters water equivalent (m w.eq.) (Mayo and others, 2004; Josberger and others, 2007). Point values of mass balance have been measured at three fixed locations, known as index sites, since 1966. Discontinuous measurements have been made at other sites throughout the period of record and are used to constrain the results.

Gulkana Glacier (fig. 1) lies in a 31.5-km^2 basin on the south flank of the eastern Alaska Range in a continental climate regime (Josberger and others, 2007). In 2009, it has an areal extent of 15 km^2. The accumulation area consists of four adjacent cirques, with east, south, and west exposures, which reach elevations as high as 2,470 m. Ice in the ablation area flows south-southwest, and the terminus is heavily covered with rock debris below 1,160 m. Point values of mass balance have been measured at three fixed index sites since 1966. The seasonal mass balance amplitude is about 1.5 m w.eq., significantly smaller than Wolverine Glacier’s seasonal amplitude. Discontinuous measurements have been made at other sites throughout the period of record and are used to constrain the results.

The calculation of a mass balance is the only way to directly determine a glacier’s response to climate. Other measurement methods, such as recording glacier surface elevation changes, do not isolate the climate signal in the way that ground mass balance measurements do. A better understanding of glacier response to climate forcing is critical to accurate forecasting of near-future global sea level rise (Meier and others, 2007) and water resources. Additionally, mass balance results are extensively used in energy balance

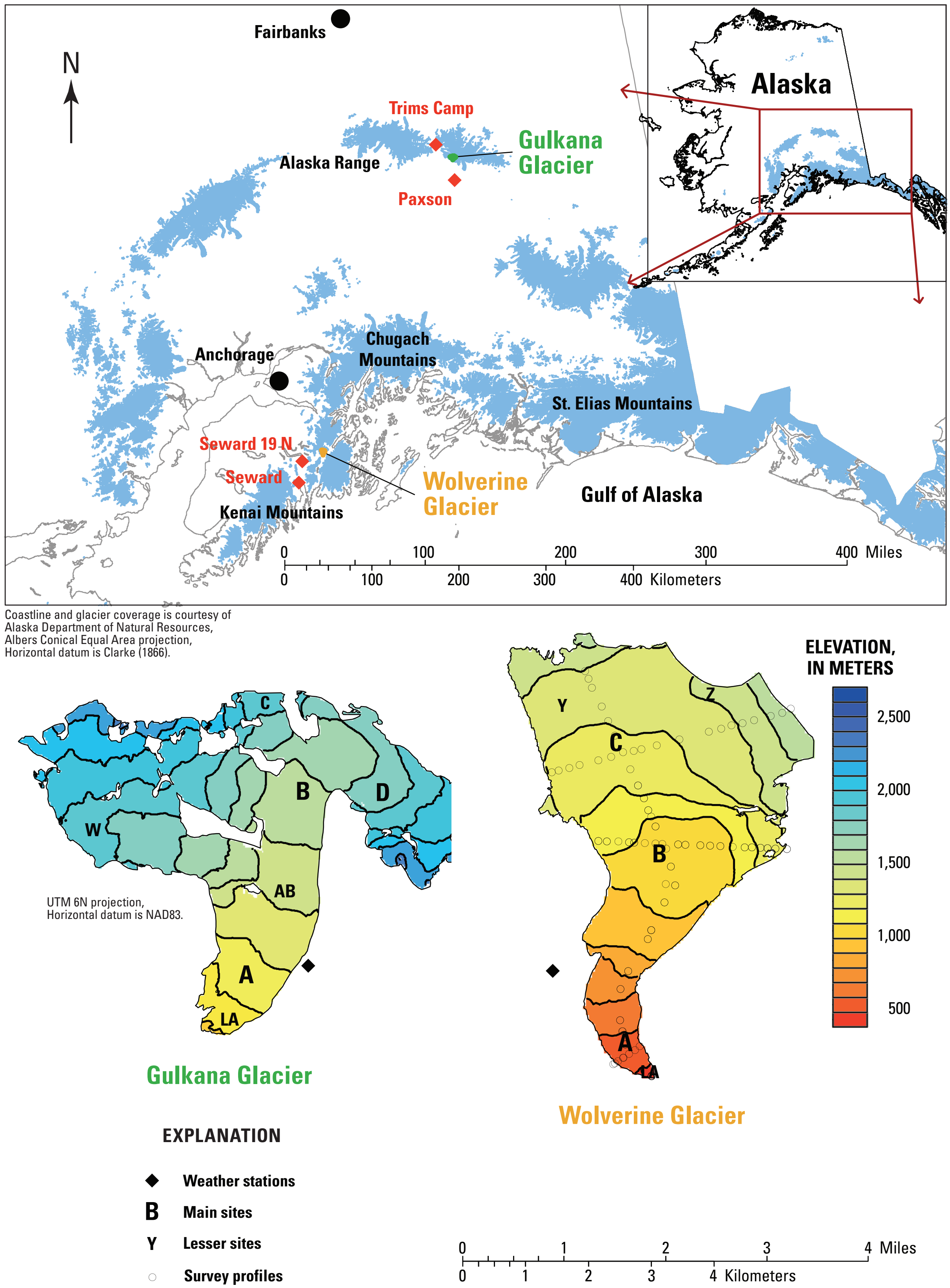

Figure 1. Gulkana and Wolverine Glaciers, with detailed maps that include the locations of the weather stations (diamonds), index sites (letters), and 1999 and 2002 margins, respectively. The profiles for the Wolverine Glacier volume surveys of 1974, 1985, and 2007 also are marked.

models applied over regional to global spatial scales (for example, Sicart and others, 2008), play a key role in dynamic ice flow modeling where mass balance must be described (for example, Paterson, 1994), and provide essential ground-truth for applications of remote sensing to glacier mass-balance changes (Chen and others, 2006; Luthke and others, 2008). The response of glaciers to climate change constitutes one of the largest uncertainties in modeling Earth's changing climate system, understanding past climate variation, making projections of future climate, and implications for climate change (Intergovernmental Panel on Climate Change, 2007; Truffer and Fahnestock, 2007; Price, 2009).

The purpose of this report is to provide the glaciological community results from a re-analysis of the Alaskan Benchmark Glacier Program measurements, which was undertaken to remove any inconsistencies or biases in the mass balance record. Our intent is to distribute what we consider the fundamental input necessary to calculate a time series of mass change using weighted index-site method (March and Trabant, 1996). We release results that utilize consistent and systematic methods over the entire available record for both glaciers. We describe our methods in re-constructing this input series, as well as our data processing methods to obtain the output time series of mass balance. Our input and output data are described in appendix A and are published here so they may be interpreted, reproduced, and/or re-analyzed with minimal effort.

Study Methods

This report describes field and analytical methods used in the Alaskan Benchmark Glacier Program. Analysis of data from Gulkana Glacier follows familiar methods, but we found a two-step analysis process was required to yield robust results at Wolverine Glacier. Consequently, we describe common methods and present initial results for Wolverine Glacier that triggered the second step. The final results are presented after all methods are described.

All point balances are given in units of meters water equivalent (m w.eq.). Field measurements of stake height and material density are not given, because each measurement required individual consideration to arrive at the values of water equivalent published here (for example, stake lean and occasions of multiple stakes representing a single site). These input values can be considered final estimates of point balance and should be used for any further analysis and interpretation.

The results of our analyses (output) consist of estimates of glacier-wide average balance for both glaciers over the period of measurement. We report these balances in two commonly used reference frames – the "conventional" balance and the "reference-surface" balance (Elsberg and others, 2001; Harrison and others, 2009). Conventional balances are given in a fixed-date system over the water year (Oct. 1–Sept. 30) and on a more commonly used floating-date system (sometimes called annual and net balances, respectively). Users not familiar with glacier mass-balance terminology are encouraged to refer to Hooke (2005), and Ostrem and Brugman (1991).

Collection and Analysis of Point Balance Data

Field trips are made 2–3 times yearly to measure and maintain reference stakes at three index sites at each glacier. Additional measurement sites are established intermittently. During each visit, the stake length from the glacier surface (ice, snow, or firn) to the top of the stake is measured and differenced from previous measurements to determine changes in elevation of the glacier surface. When the surface material lost its ice, we assume a density of 900 kg/m^3. The calculation of the balances of snow and firn requires measurement of a density profile by either snow-pit or snow-core methods (Ostrem and Brugman, 1991). An average density is calculated for the material, and a water equivalent layer thickness is determined for the change in mass measured. In rare cases, measurements were not made and density was estimated from previous measurements.

Field visits commonly are made in the spring at the onset of the melt season and again in early autumn near its completion, so that direct measurements closely reflect maximum winter snow balances and net balances at each location. However, the timing of the melt season varies year-to-year and site-to-site, so these measurements seldom reflect the maximum winter snow or net balance. Melting often occurs at the low elevation sites after our autumn visits (equivalently before spring visits), and new snow has often fallen at the high elevation sites before our autumn visits. New snow at a site must be accounted for in the following balance year as it represents a mass change after the close of the current net balance year. Similarly, any melting of the ice surface between autumn and spring visits must be transferred to the preceding year, as it represents a mass loss in the previous net balance year. These values are explicitly indicated in the data files.

Although uncommon, stakes occasionally have been lost or otherwise unaccounted for. Never has a glacier visit occurred without at least one site measurement being made, thereby allowing values for missing data to be interpolated using the history of balance gradients. The interpolation is completed by fitting a polynomial to the distribution of all point balances as a function of elevation, as shown in figure 2. The shape of this glacier-wide mass-balance gradient is subsequently translated to best fit the yearly-measured values, which enables construction of an interpolation curve for missing data. A list of the interpolated values is provided in table 1. We note that each glacier's polynomial fits its point balances with an R^2 correlation coefficient of 0.99. Assuming a constant balance gradient results in poorly defined additional uncertainty in actual balances, but we do not have enough data to justify a more complicated method or to quantify errors.

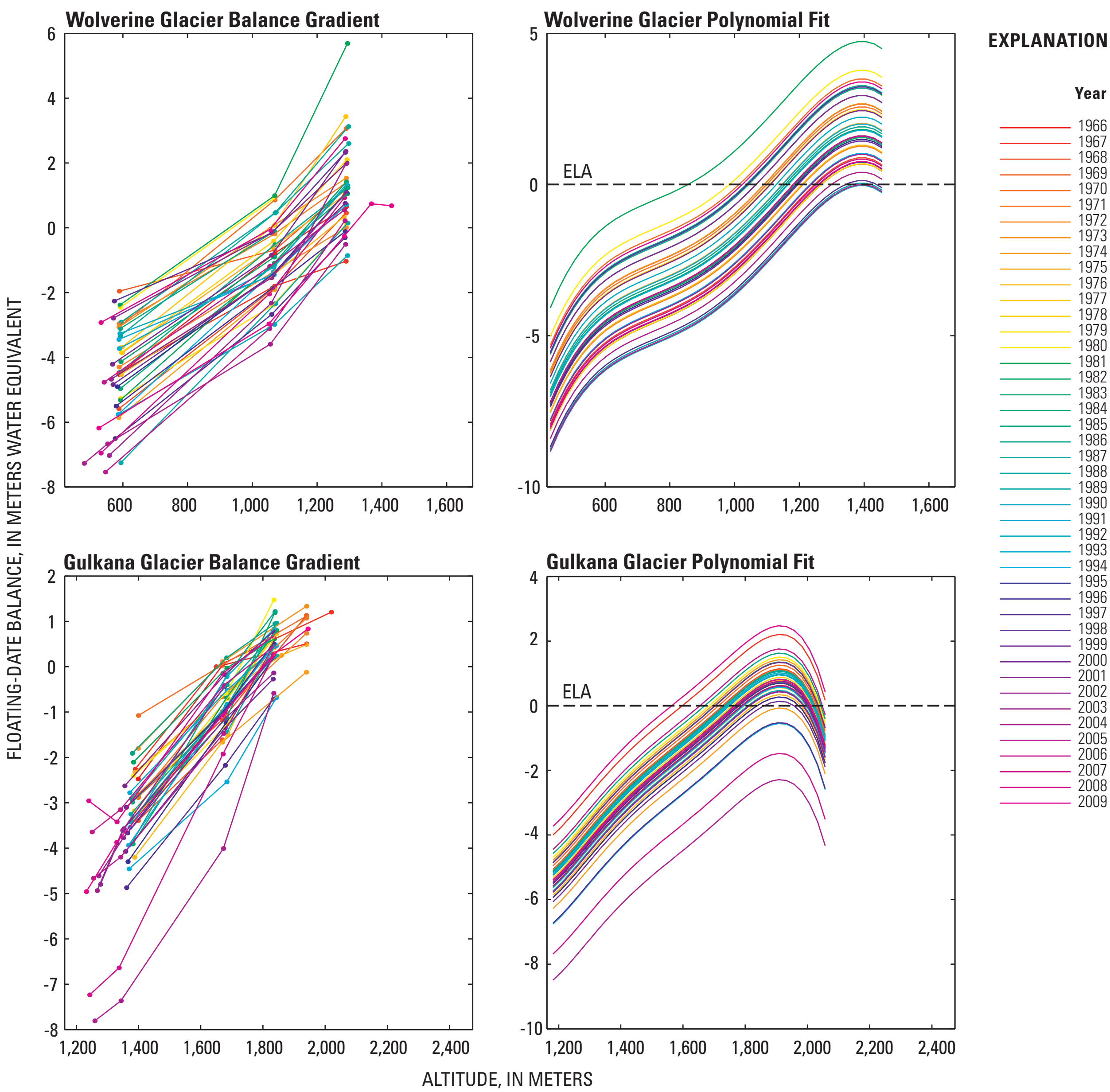

Figure 2. Mass-balance gradients for every available year, constructed using a polynomial fit. Panels on left side show actual data and panels on right side assume a constant, best-fit shape and are the curves used to interpolate missing data. The x-axes range from the terminus of each glacier to its head.

Table 1. Site-years requiring mass-balance gradient interpolation for net balance due to missing or otherwise inadequate data.

[Location of sites is shown in figure 1]

Gulkana Glacier		Wolverine Glacier	
Year	Site	Year	Site
1969	C	1974	C
1974	A	1980	C
1989	A	1985	C
2003	D	1991	C
		1994	C

Collection and Analysis of Meteorological Data

A weather station was installed on each glacier margin during the early years of the study program to measure air temperature and precipitation catch (Mayo and others, 1992; Kennedy, 1995; Kennedy and others, 1997). Original analog temperature sensors were replaced during 1996–98 with more accurate digital sensors. Overlap between the two sensors shows a bias, which was corrected by adding 1°C to the analog records (March and O'Neel, 2010). We use a wet adiabatic lapse rate of -6.5°C /km to scale temperature data from low to high elevations. We choose not to use a modeled daily lapse rate, because in our case, changing the lapse rate does not affect the balance very much (Gardner and Sharp, 2009). Both station records contain data gaps; approximately 7 percent of the data is missing (ignoring the years 1966 and 1967 before the glacier weather stations were installed). Precipitation gauges do not have perfect catches, and gauge catch efficiency of <50 percent is expected. We assume precipitation as snow at each index site is proportional to the gauge catch. A precipitation/catch ratio is determined by linear regression analysis between cumulative-seasonal snowfall and site-modified cumulative-seasonal gauge catch. Site-modified cumulative-seasonal gage catch includes only precipitation that fell when temperature was sufficiently cold to snow.

We use linear best-fit relationships to extrapolate from the nearest National Weather Service station to fill most existing gaps in the records. To evaluate performance of this step, we correlated values during periods of overlap. Temperature correlates well; precipitation does not correlate as well, but regional climate models do not fare any better in predicting precipitation at the glaciers. At Wolverine Glacier, the nearest weather stations are Seward (1965–86) and Seward 19 N (1987–2010), whereas Trims Camp (1965–78) and Paxson (1979–2010) are the closest operating stations to Gulkana (fig. 1). In the extreme case that no nearby data is available (<0.5 percent, see files *Glacier_temp* and *Glacier_precip*), the average daily value for all existing years is applied.

Choosing the closest operating weather station to fill gaps in the glacier weather record may not always be the best option. Alternatively, an average of several multiple regional stations or downsized climate model data could be used. (Downsizing involves using statistical methods to make general climate models have regional prognoses). During periods of overlap we found no improved relation with glacier data when averaging several stations. Climate model downsizing is a complication we do not wish to implement. We note that the meteorological data are used only to model short time periods around the minimum and maximum of the balance year to find the timing these events.

Calculation of Glacier-Wide Mass Balances

We continue to rely on the index method (March and Trabant, 1996) to calculate glacier-wide average mass balances. The glacier surface area is partitioned into three "bins" by altitude, equal to the nominal number of measurement sites. Each index site was originally located at the median altitude of the bin, and is assumed to represent the average balance for that bin. Each point balance is scaled by the site's bin area, and the sum of the bin balances gives the glacier-wide balance. Both fixed- and floating- date glacier-wide mass balances require short-duration degree-day modeling (described later). The model is run at each site to determine the timing and magnitude of the yearly mass extrema in the floating-date system, and to determine the end of year annual balance in the fixed-date system. We calculate the glacier-wide balance on a daily basis from the earliest *site* minimum date to the latest site minimum date to determine the timing and magnitude of the yearly *glacier-wide* minimum mass or glacier-wide net balance.

Floating-date balances are given as both reference-surface balances and conventional balances (Elsberg and others, 2001; Harrison and others, 2009). Integration over a fixed-geometry gives the reference-surface mass balance. We use the geometry of the first year of measurement (1966) as the reference-surface. Conventional-balance estimates require routine updates to the glacier geometry. Photogrammetric analysis of stereo pairs of vertical aerial photographs allowed extraction and gridding of the surface geometry (Digital Elevation Models, DEMs) at irregular time intervals through the program (table 2; see Cox and March, 2004, for Gulkana Glacier photogrammetric analysis). An area altitude distribution was constructed for each DEM, and geometric updates were applied annually, using linear interpolation between DEMs. In both balance systems, elevation bins, which are allocated about each index site, are re-partitioned each year on the basis of changes in the hypsometry of the site. In the case of the reference surface balance, this effectively projects the measured balances onto the reference surface (Harrison and others, 2009).

Table 2. Photogrammetric data (aerial photography and associated DEM) provide time variable AADs and also are used to make measurements of volume change.

[Measurements must be adjusted to the minima of the seasons; adjustments are given in the ablation adjustment column. Errors are ±0.7 for Gulkana Glacier and ±2.1 for Wolverine Glacier. All values are in meters water equivalent]

Gulkana Glacier			Wolverine Glacier		
Photography date	Ablation adjustment	Photograph cumulative	Photography date	Ablation adjustment	Photograph cumulative
09-07-1974	-0.2049	0	08-03-1979	-1.9898	0
07-11-1993	-1.7552	-7.5503	09-27-1995	0	-.1542
08-18-1999	-.1667	-11.6618	09-24-1998	-.0149	-2.7011
			08-26-2002	-.3613	-2.2415

A degree-day model (Johannesson and others, 1995) is necessary for calculating glacier-wide balances in both the conventional and reference surface frames. Our model estimated change in mass in each bin on a daily time step, relying primarily on air temperature and precipitation recorded at the glacier margins. The glacier gains mass when solid phase precipitation accumulates on it. Temperature is used to determine the phase of precipitation at each site: a temperature less than 0 ºC indicates precipitation in the form of snow, and temperatures greater than 1.7 ºC indicate rain. The fractional phase is linearly interpolated between the two temperatures, so that between 0 ºC and 1.7 ºC precipitation is snow of which a fraction is melting (U.S. Army, 1956). As discussed earlier, gauged snowfall is scaled to each site by pre-determined ratios of gauged precipitation and measured accumulation at each index site (previous values from March 2000; Mayo and others, 2004; table 3) derived through linear regression (approximately 60 data pairs for each site).

Melting occurs when temperatures rise above 0 ˚C. The magnitude of melt is computed by calculating positive degree-days (PDD, or P) and using degree-day factors for snow (k_s) and ice (k_i) separately determined at each glacier (previous values from March, 2000; Mayo and others, 2004; table 4). We used a free-knot spline method (Shea and others, 2009) with all 44 years of temperature and melt data from each site (approximately 190 data pairs for each glacier) to resolve the factors. This method gives a best-fit solution for snow and ice melt coefficients simultaneously by fitting two linear regression lines to the data, with the connection between the lines (the knot) allowed to move freely to its optimal location. The resulting data fits have R^2 values equal to 0.90 for both glaciers.

Table 3. Ratios between measured precipitation at the weather station and measured snow at each site are resolved using linear regression to determine a single value for the entire measurement period.

[Location of sites is shown in figure 1. At Gulkana Glacier, previously determined ratios were allowed to change yearly, thus they span a broad range of values (March 2000). Previous ratios for Wolverine Glacier represented 10-year site-averages centered on 1973 (Mayo and others, 2004)]

Gulkana Glacier				Wolverine Glacier			
Site	New ratio	R^2 value	Previous ratio	Site	New ratio	R^2 value	Previous ratio
A	1.12	0.83	1.4 to 4.0	A	2.35	0.57	1.41
B	1.6	.91	1.4 to 4.0	B	2.89	.9	2.71
D	2.56	.82	1.4 to 4.0	C	4.83	.92	3.69
C	2.04	.92	1.4 to 4.0				

Table 4. Melt rates for snow and ice.

[At Gulkana Glacier, previously determined ratios were allowed to change every melt season, thus they span a broad range of values (March 2000). At Wolverine Glacier, previous ratios represented 10-year site-averages centered on 1975 (Mayo and others, 2004). All values are in millimeters water equivalent per degrees Celsius per day]

Gulkana Glacier				Wolverine Glacier			
Material	New rate	R^2 value	Previous rate	Material	New rate	R^2 value	Previous rate
snow	-2.4	0.9	-3.5 to -5	snow	-3.1	0.9	-4.5
ice	-5.9		-7.0 to -10	ice	-4.7		-4.5

The surface must be adjusted to the end of season geometry using the degree-day model. In order of decreasing effect, the degree-day model is used to increment the profile-based volume-change estimates, the photogrammetric measurements, and the stake data. The profile-based estimates will be discussed in subsequent sections.

Deviating somewhat from historical USGS benchmark glacier reports, but better conforming to the mass balance community as a whole, this report focuses on surface mass balance. Although previously included in USGS reports (March, 2000; Josberger and others, 2007), we chose to exclude internal accumulation and ablation because of large uncertainties inherent in calculating these values. Measurements of summer surface temperatures and runoff required to estimate these terms have not been performed consistently. Also, there is no consensus on how to include internal terms in the balance calculations. Previous estimates of internal accumulation and ablation indicated they were of similar magnitude, effectively summing to no more than their errors. For those interested, we have included these internal terms in a separate time series of mass balance (file *Glacier_float_CONVsubSurf*), but they are not shown in the figures published here. Errors shown in the mass balance figures do not include the potential errors that arise from estimating or neglecting internal accumulation and ablation.

Calculation of Preliminary Cumulative Balance

Glacier-wide balances are integrated over the project history to produce a cumulative balance time series (for example, Hooke, 2005). Improved confidence in the results can be obtained by comparing the time series of conventional balance to photogrammetric volume change estimates (Ostrem and Brugman, 1991; Cox and March, 2004). Good agreement indicates repeated precision in the magnitude of balance estimates. Photogrammetric measurements are available for Gulkana Glacier in 1974, 1993, and 1999; measurements for Wolverine Glacier are available for 1979, 1995, 1998, and 2002 (table 2). A comparison of raw field data and photogrammetric data for Wolverine Glacier indicates that field data alone cannot resolve meaningful balances even with error bars considered (fig. 3), since observation shows the glacier melting but the data show positive balances. We need to further constrain field data to obtain a reliable balance history at Wolverine Glacier.

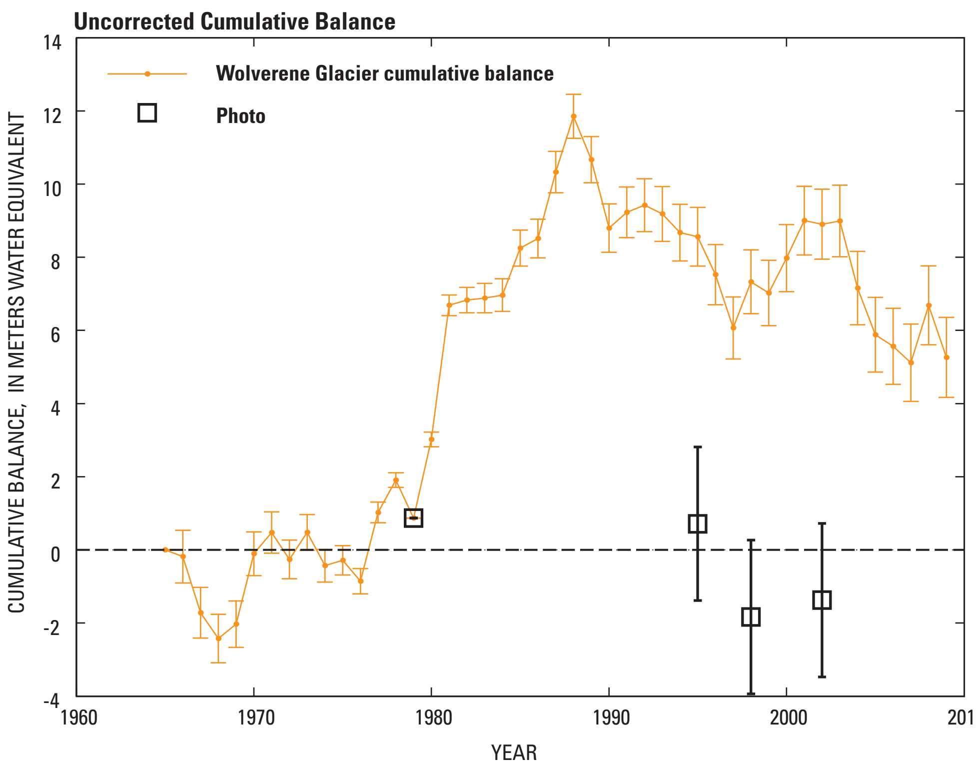

Figure 3. Preliminary cumulative (conventional) balance time series for Wolverine Glacier exhibits positive values over the duration of record in contradiction with observed thinning and retreat, demonstrating the need for a correction procedure. Photogrammetric data (black) are relative to their first year of measurement.

Additional Methods Required for Wolverine Glacier Data Analyses

When analyzed with the index method, the cumulative mass balance series for Wolverine Glacier does not agree with balances derived from photogrammetric measurements, nor does it agree with balances calculated on the basis of direct observations of overall glacier thinning and retreat during the program. The index method yields a cumulative balance of approximately +5 m w.eq. (fig. 3), in contrast to photogrammetric measurements that indicate a negative cumulative balance. All previously published net balances included an additive correction term of -0.48 m w.eq., which was applied annually to remedy the inconsistency. Previously published winter balances were not corrected (Josberger and others, 2007; Harrison and others, 2009). The correction was required as a consequence of volume change estimates made in 1974 and 1985 on the basis of repeat surveys of cross flow and longitudinal profiles of surface elevation (Mayo and others, 1985). The average yearly balance at Wolverine Glacier is 0.12 m w.eq., so the correction is about 400 percent of the value. This large correction prompted renewed investigation of the issue. A third survey, made during 2007, re-occupied some sites with GPS. The three surveys are marked in figure 1.

We present results of the third survey and a re-analysis of the original survey, using consistent methods in both cases. These results greatly improve the correction process for the raw data. Volume change estimates are made for both periods by fitting a polynomial to the distribution of elevation change as a function of altitude (fig. 4). Using the degree-day model and mass maximum estimates, we adjusted each surface to a mass minimum before differencing adjustments so that volume change estimates before differencing correspond to common timing of surface evolution (table 5).

Table 5. Field campaign surveys were used to measure volume change of Wolverine Glacier independent of photogrammetric estimates or stake networks.

[Differencing of the surfaces generated by the measurements requires that they be adjusted to represent the glacier surface at the time of minimum mass. Survey dates are closer to the occurrence of maximum mass than minimum mass. We minimize dependence on the degree-day model by adjusting to the mass maxima, then subtracting the summer balance to get the minima. Surface differencing then yields the cumulative volume change. All values are in meters water equivalent]

Volume change period	Optical survey campaign date	Ablation adjustment	Optical survey cumulative
Period 1	03-12-1974	-2.3648	0
	06-10-1985	-1.4301	4.5715
Period 2	06-10-1985	-1.4301	0
	04-26-2007	-2.6494	-13.4458

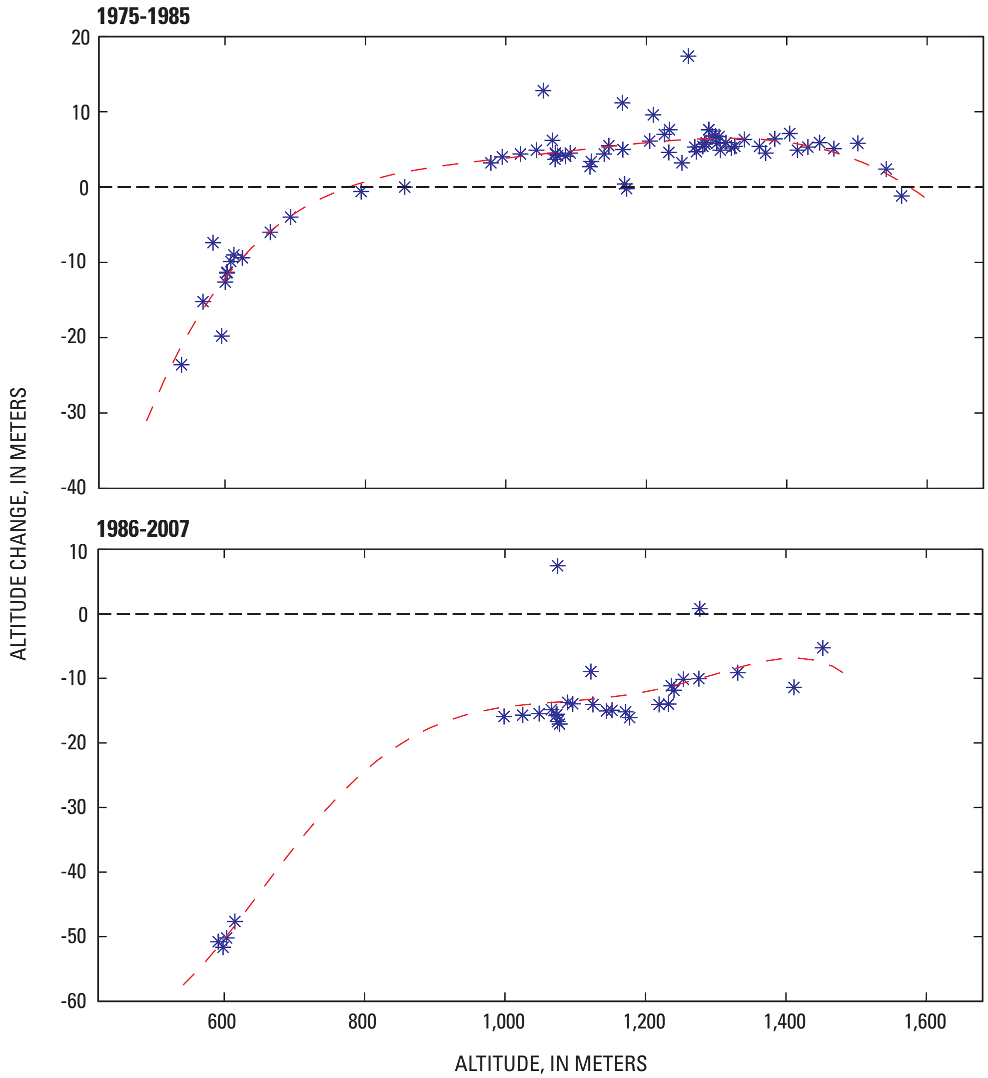

Figure 4. Polynomial fits to optical survey data used to calculate Wolverine Glacier volume change during balance years 1975–85 and 1986–2007. Negative values indicate volume loss. The x-axes range from the terminus of the glacier to its head.

Balance gradients resulting from the extensive site networks in 1966–67 (Tangborn and others, 1977; Mayo and others 1985) show that winter accumulation is highly variable over the lower glacier, with anomalously high accumulation (large drifts) at the two lower measurement sites. An extensive longitudinal probe survey in spring 2009 gave similar results, suggesting that this phenomenon is quasi-stable in time. Anomalies like this are expected under such limited sampling (Fountain and Vecchia, 1999), but we find utility remains in the data.

We developed a procedure to adjust field measurements so they better match photogrammetric data, using the independents profile-based volume change estimates. Short-term variability is thus described by field observations, while secular trends and magnitude are obtained and verified with photogrammetric estimates of volume change. Our strategy to correct the field measurements combines the knowledge that the discrepancy arises from local accumulation anomalies with profile-based estimates of volume change to scale winter balances at the lower sites before estimating glacier-wide balances. In other words, we seek a correction factor that provides the best match between balances derived (calculated?) from measurement made at stakes on the glacier balances derived from photogrammetric measurements.. This strategy retains independence of the photogrammetric measurements so that they can be used to verify the magnitude of the cumulative time series.

For clarity, we illustrate the method by considering a hypothetical year in which a glacier-wide balance based on measurements at a single stake differs greatly from a balance based on a better-constrained estimation of volume change. We proceed to correct the stake estimate to the volume change estimate as follows:

The balance as determined by volume change is represented as $\overline{b}_n^*$ with unknown (small) error ε. The volume change balance is equal to a function of the stake-measured balance,

$$\overline{b}_n^* + \varepsilon = f(\alpha, \beta)\,, \tag{1}$$

where β is the desired correction factor and α is a Boolean variable signifying whether sufficient positive degree-days occur to force the transition from melting snow to melting the ice beneath. We cannot solve for $f(\alpha, \beta)$ exactly, but obtain the optimal solution in terms of minimizing ε.

The volume change balance is equal to the sum of the adjusted stake winter balance $\overline{b}_w^*$ and summer balance $\overline{b}_s^*$. Because we have only one (hypothetical) stake, $\overline{b}_w^* = \overline{b}_s^*$ and $b_w^* = b_w^*$ and $\overline{b}_s^* = b_s^*$. Thus

$$f(\alpha, \beta) = b_w^* + b_s^* \tag{2}$$

We need to express the right-hand-side of equation (2) in terms we know and the unknowns α and β. Because the desired correction is based on the observation of anomalous snow, the first term is measured winter stake balance corrected by unknown β:

$$b_w^* = \beta b_w\,. \tag{3}$$

The adjusted summer balance (second term of equation (2)) can be written as a function of degree-day parameters. We break the total positive degree-days (P) into those that melted snow (P_s) and ice (P_i) so $P = P_s + P_i$. Using degree-day melt-factors for snow and ice (k_s, k_i), the adjusted summer balance becomes:

$$b_s^* = k_s P_s + k_i P_i\,. \tag{4}$$

The variables P_s and P_i are functions of α and β. First, suppose that we do not have sufficient positive degree-days to transition from melting snow to melting the ice beneath. Then $P_i = 0$ and $P_s = P$ so

$$b_s^* = k_s P \text{ for } \alpha = 0\,. \tag{5}$$

When ice does melt, α = 1. Adjusted accumulated snow ($\beta\, b_w$) all melts. The number of degree-days melting snow, and consequently ice, is

$$\begin{aligned} P_s &= \frac{-\beta b_w}{k_s} \\ \Rightarrow P_i &= P - \frac{-\beta b_w}{k_s} \text{ for } \alpha = 1\,. \end{aligned} \tag{6}$$

If we substitute equation (6) into equation (4) and simplify, we get

$$\begin{aligned} b_s^* &= \beta b_w + k_i P - \frac{-k_i \beta b_w}{k_s} \\ &= \beta b_w \left(\frac{k_i}{k_s} - 1 \right) + k_i P \text{ for } \alpha = 1\,. \end{aligned} \tag{7}$$

Substituting equations (3), (5), and (7) into equation (2)

$$f(\alpha, \beta) = \beta b_w + (k_s P)\left[1 - \alpha\right] + \left(\beta b_w \left(\frac{k_i}{k_s} - 1 \right) + k_i P \right)\left[\alpha\right] \tag{8}$$

To solve for β (and α), we utilize the meteorological data and get P. The volume change $\overline{b}_n^*$ and stake measurement b_w, are obtained in the field. We have previously obtained k_s, k_i. Equation (8) is solved with the following optimization problem:

$$\min_{\alpha,\beta} \left\| \overline{b}_n^* - f(\alpha, \beta \right\|_2^2\,, \tag{9}$$

$$\text{such that } \alpha = \begin{cases} 1 \text{ if } \beta \mathrm{b}_w < k_s P \\ 0 \text{ if } \beta \mathrm{b}_w \geq k_s P\,. \end{cases} \tag{10}$$

The constraints (10) equate the value of α to 1 if the amount of snow is less than the total degree-days times the snow melt-factor, that is, if we melt all the snow. The solution space for this optimization problem with Boolean constraints ((9)-(10)) is small, making a brute force approach possible. We use the MATLAB© function "fminbnd", which finds minimums of single-variable functions on a fixed interval (Forsythe and others, 1976), to solve equation (9). The constraint equations (10) are set up as logical functions. For more details on these types of problems, see Creignou and others (2001).

The process of solving for β is more complex than described in this simplified example. We resolve a unique α each year at every site, but we determine β only once over each of two intervals of volume change estimates. To finalize the correction, β must be scaled by a site-specific over-accumulation factor. Each site's factor was based on the extensive stake networks deployed during 1967 and the 2009 centerline snow probing. We assigned constant over-accumulation factors of 1 to site A, 1.5 to site B, and 0 to site C. [Note this results in no adjustment to values at site C]. In practical terms, the correction is carried out using the following procedure:

- Determine uncorrected b_w and P from site measurements and ablation model.
- Estimate balances $\overline{b}_n^*$ for two periods, 1975–85 and 1986–2007, with repeat field volume change surveys.
- Assign constant over-accumulation factors for each site based on extended state network and probe surveys.
- For each interval of surveyed volume change, find optimal β using equation (9).
- Adjust seasonal balances by scaled β's. Adjustments to winter balances result in small changes to summer balances because the timing of transition from snow to ice changes.
- Recalculate net balance using corrected seasonal balances.

We note that this correction needs to be applied only to data from Wolverine Glacier. At Gulkana Glacier, balances determined from field measurements generally agree with those calculated from photogrammetric measurements (Cox and March, 2004).

Results of Data Analysis

The cumulative net mass balance time series for both glaciers in conventional and reference-surface frames over the lifetime of the project are shown in figure 5. Adjusted data are shown for Wolverine Glacier. Error bars assume a glacier-wide average error of 0.2 m and are reset at the first photogrammetric volume change solution (Cox and March, 2004). Both glaciers exhibit a long-term trend of mass loss, although losses have not been monotonic for Wolverine Glacier. Large parts of both glaciers have become thinner, and each glacier has retreated since the inception of the program. Rates of mass loss have accelerated in the past decade. Wolverine Glacier required special consideration (tables 5 and 6), but in general, our methods are now consistent between glaciers over the entire time series, providing results that are comparable between the two glaciers. General trends in the data are similar to those reported in earlier publications (for example, Josberger and others, 2007), indicating that conclusions of previous publications based on the variability of the mass balance are not erroneous. Both glaciers are undergoing sustained mass loss, and the rate of mass loss is increasing in time.

The re-analysis data exhibits some marked changes when compared to the previously published results (for example, Josberger and others, 2007; Harrison and others, 2009). Figure 6 shows the difference between our estimates of net balance and the previously published time series for each year. Differences in the balances calculated by the two methods arise from the following situations, in order of decreasing magnitude:

- Several large errors in the field data were identified and corrected.
- We developed a new correction procedure for data from Wolverine Glacier.
- We re-calculated the degree-day model with new constants.
- Missing values were interpolated from balance gradient curves. Details of how missing data were previously estimated are not well known.
- We introduced a new method of solving for the glacier-wide mass minimum, which changes the date on which the net balance uses as the glacier-wide minimum-date.
- Our estimates do not contain internal balance terms.

Table 6. Accumulation at Wolverine Glacier's lower sites is multiplied by period factor β.

[Field observations suggest that raw data for site C is valid but data for sites A and B need to be scaled. We decide site C is good (0), A is bad (1), and B is 1.5 times as bad as A, which gives these per-site factors]

Correction period	Period factor β	Site A factor	Site B factor
1966–1985	0.4878	0.8781	0.5854
1986–2009	.4156	.7481	.4988

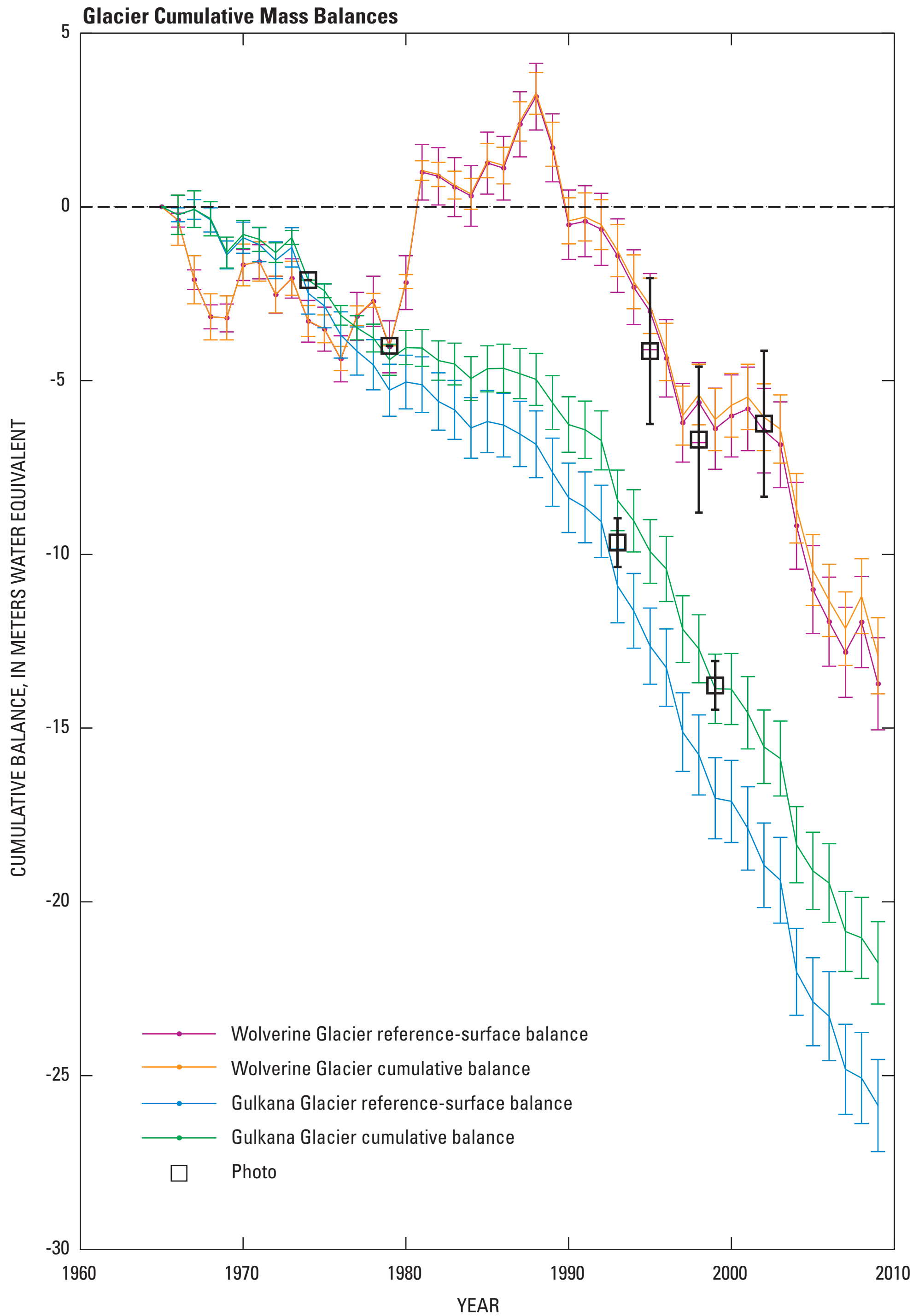

Figure 5. Cumulative balance time series presented in both conventional (blue, orange) and reference-surface (green, purple) frames for both Gulkana and Wolverine Glaciers, using adjusted data for Wolverine Glacier. Error bars represent error propagation assuming a 0.2 m/yr error in glacier-wide balance. Photogrammetric data (black) are relative to their first year of measurement. Positive values indicate mass gain, negative values mass loss.

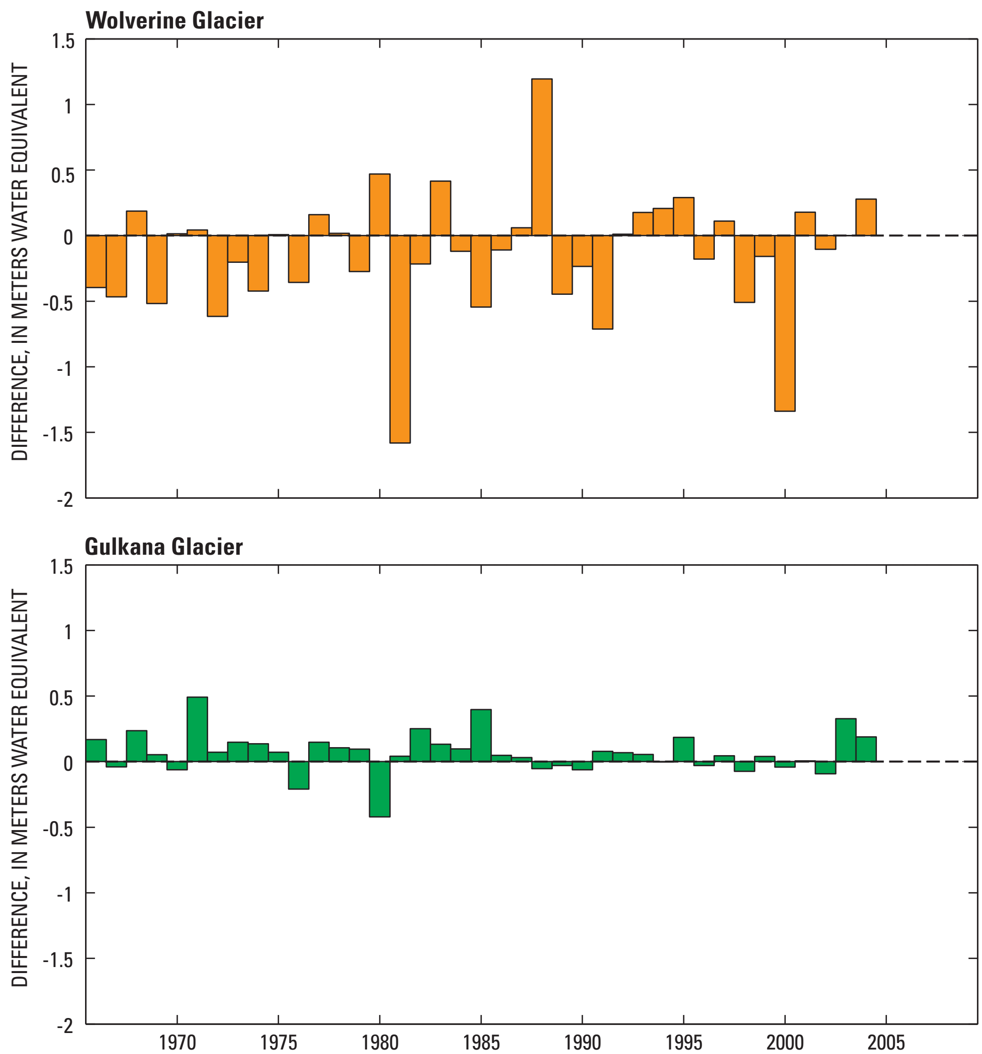

Figure 6. Differences between previously published and (re-analyzed) conventional balances. Positive values indicate that the previously published balance was larger than the new value. A negative value indicates the new balance is larger than the previously published value.

The output of the three-site index method remains highly sensitive to the input variations, especially for the high elevation site. This is because the hypsometry of both glaciers is such that most of their areas are at high elevation.

When comparing the previously published series to the re-analyzed series, we see that all differences at Gulkana Glacier are small (< 0.5 m w.eq.), but larger differences exist at Wolverine Glacier (fig. 6), which are accounted for in detail here.

- Errors in the earlier reduction of the data for 1981, 1988, and 2000 for site C have been found; site C dominates the glacier-wide balance for those years.
- Data for site C is missing for 1991 (table 1) and has been interpolated from the balance curve. The other missing values dealt with in this manner also are listed in table 1, but they did not affect as great a change in balance as did the interpolated data for site C.
- The two upper index stakes were lost in 1967, but an extensive network of extra stakes (other than the usual three stakes) was installed in this year. A map of late summer balance (Tangborn and others, 1977) allows us to estimate the balance with greater confidence than was possible using a gradient extrapolation. Qualitative descriptions of the weather at Wolverine Glacier in 1967 provide greater confidence that the updated value captures the annual variability in balance experienced that year.

Conclusions

This re-analysis of data from Wolverine and Gulkana Glaciers has identified several strong and weak properties of the existing dataset. This discovery, taken together with current understanding of glacier response to climate forcing, mandates changes to the data-collection program. The lower elevation index sites at both glaciers are at risk of being lost to retreat or stagnation of the ice, and the upper sites are no longer guaranteed to be in the accumulation area of the glacier. Efforts are being made to re-define appropriate index sites through an expansion and upward migration of the site networks in attempts to return (closer) to the original partitioning of the area represented by each stake. Realization of the sensitivity of estimated balances to sparse input data is motivating deployment of expanded stake networks, which will better define the shape and stability of the balance gradient. Modernization of weather stations is underway, and temperatures are being measured on the glacier to better determine lapse rates and microclimates responsible for controlling glacier mass balance. Analysis and comparison of balance gradients instead of site-partitioned bins (the index method) to resolve glacier-wide balance differences will be presented in a planned future report.

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Appendix A. Description of Input and Output Data

Data

Analysis Inputs

We provide all input and output data with the report, and establish our file naming convention here. Data files are named *Glacier_data*, where *Glacier* can take the value Gulkana Glacier or Wolverine Glacier. The *data* field provides rudimentary description of the data in the file. A more detailed description of each file, including column headers and units, is provided in the file *Glacier_README*.

Measured point balances are given in a separate file for each glacier. Each year, we provide the dates of the spring and autumn visits along with point balance at these times. Because measurements are rarely made at the exact time of the local mass minimum, we commonly record components of the balance that must be transferred to a subsequent year during our field visits. For the j^{th} year, data recorded as spring mass represents a lowering of the summer surface since the previous autumn measurement (common at lower sites) and is added to the j^{th} -1 year. Data recorded as autumn mass represents new snow on top of the summer surface (common at high sites), which is subtracted from the j^{th} year. The altitude of each site is the average of the measured site altitudes on the two visits.

These data are presented in the files *Glacier_input_balances* and represent the fundamental input to our analysis, as well as any future analyses. Seasonal point balances that were missing and were filled in by interpolation of the balance gradient curve are highlighted. Values in pink and blue represent net balance and winter balance estimates, respectively, that were made via balance gradient interpolation. If the spring observation of the previous summer surface or the fall observation of new snow does not exist, these values are estimated by the degree-day model and highlighted in orange. Similarly, fall adjustments are highlighted in purple. The data presented for the lower sites (A, B) at Wolverine Glacier have not been corrected for the known accumulation issue so that this problem can be addressed by others using their own preferred method. If ASCII files are desired, the file can be resaved in a text-only format and the highlighting will disappear.

Area-altitude distributions are presented in the files *Glacier_AAD*. Local values of daily temperature and precipitation are tabulated in the files *Glacier_temp* and *Glacier_precip*. If the data are missing, a value is estimated from the nearest National Weather Service meteorological station record. These values are highlighted. Again, if ASCII files are desired, the file can be resaved in a text-only format and the highlighting will disappear.

Analysis Outputs

Main output files are *Glacier_float_CONV*, *Glacier_float_REF*, and *Glacier_flixed_CONV*, *Glacier_fixed_REF*. Float files contain net balances; fixed files contain annual balances. Files label CONV contain conventional balances, and reference surface balances are listed in *REF* files. We present the timing of modeled mass site-maxima and minima for each year in the file *Glacier_SiteMaxsMins*. The equilibrium line altitude (ELA) is the last column; this is estimated from the polynomial mass-balance gradient fit. We note that the ELA is *only* from the polynomial fit and thus should be taken as *only* one of the many possibilities for an estimate of the ELA. A similar file structure to *Glacier_float_CONV* is given for balances that include internal ablation and accumulation (floating date conventional only) where the suffix *subSurf* is added.

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