USGS Alaska Benchmark Glacier mass balance data-phase 1

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Overview: This document escribes the long-term mass balance measurement campaigns at Wolverine and Gulkana glaciers.

Summary

Since the late 1950s, USGS has maintained a long-term glacier mass-balance program at three North American glaciers. Similar measurements began at Sperry Glacier, MT in 2005. Direct field measurements are combined with weather data and imagery analyses to estimate the seasonal and annual mass balance at each glacier in both a conventional and reference surface format (Cogley and others, 2011). The analysis framework (van Beusekom and others, 2010; O'Neel and others, 2014) is identical at each glacier to enable cross-comparison between output time series. Vocabulary used follows Cogley and others (2011) Glossary of glacier mass balance.

Phase one of this data release will include input and output files from the USGS Alaska Benchmark Glacier Program. Three types of input are provided for Wolverine and Gulkana glaciers: 1) time-variable Accumulation Area Distribution; 2) time series of point water balance at three index sites on each glacier (with secondary sites given in recent years); 3) weather data from stations installed along the glacier margins. Two solution sets are output for each glacier: 1)Conventional glacier-wide mass balance from direct observations; 2) Geodetically calibrated, conventional glacier-wide mass balance, which represents our preferred solution. The USGS runs an analysis code to transform the three input data to the output data that will be included in Phase three of this data release. Output data represent surface mass balance estimates. We do not account for basal or englacial accumulation or ablation. Mass balances are reported in water equivalent (w.e.) units, and often represent integration of multiple field measurements. Whenever possible, we average multiple field measurements to account for surface roughness and measurement errors. These 'unprocessed observables' will form the basis of Phase two of this data release.

Purpose

The purpose of this project is to quantitatively evaluate time changes in mass at specified glaciers.

Projection and Datum: All maps and coordinates provided are referenced to the Universal Transverse Mercator (UTM) coordinate system. Both glaciers are located in UTM zone 6N. Elevations are referenced to the WGS84 ellipsoid. EPSG:26906

Units:

The "meter water equivalent" (m w.e.), describes *glacier* mass in *specific (*per unit area) units as the thickness of an equal mass having the *density* of water. The meter water equivalent is obtained by dividing a particular mass per unit area by the density of water: 1m w.e. = 1000kg m^{-2}/ρ_W. (Cogley and others, 2011).

Wolverine Glacier
Project Start Date: April 1966
End date: ongoing

Elevation Range: Approximately 450—1680 meters
Location: Latitude: 60°24'20"N, Longitude: 148°54'16"W
Area: 16.1 km[2] (2011, O'Neel and others, 2014)

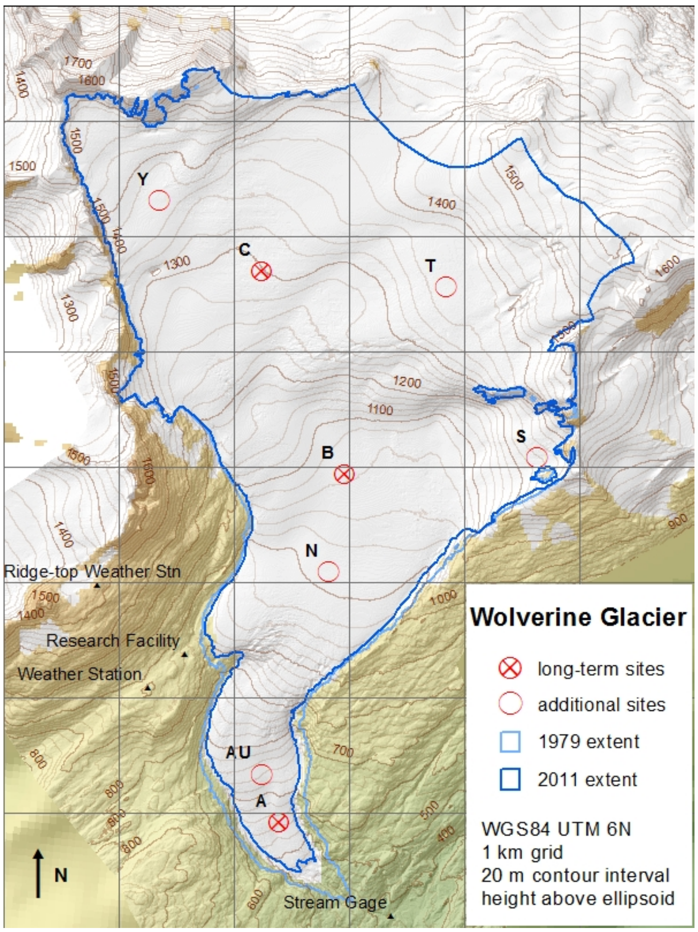

Figure 1. Map of Wolverine glacier showing location of mass balance stake sites.

Site	Easting [m]	Northing [m]
A	394387	6694920
AU	394241	6695331
B	394960	6697943
C	394237	6699700
la	394784	6694447
n	394823	6697085
p	394769	6696837

s	396632	6698076
t	395837	6699557
y	393355	6700306

Table 1. Index stake sites at Wolverine Glacier, corresponding to locations shown in Figure 1. Rows with capital letters as labels indicate primary long term sites, and lower-case labels indicate secondary and/or shorter-term sites. Site AU replaced site A in 2009 when it became inaccessible due to terminus retreat.

Gulkana Glacier

Project Start Date: April 1966
End date: ongoing
Elevation Range: Approximately 1150—2450 meters
Location: Latitude: 63°16'40"N, Longitude: 145°25'50"W
Area: 16.7 km^2 (2011, O'Neel and others, 2014)

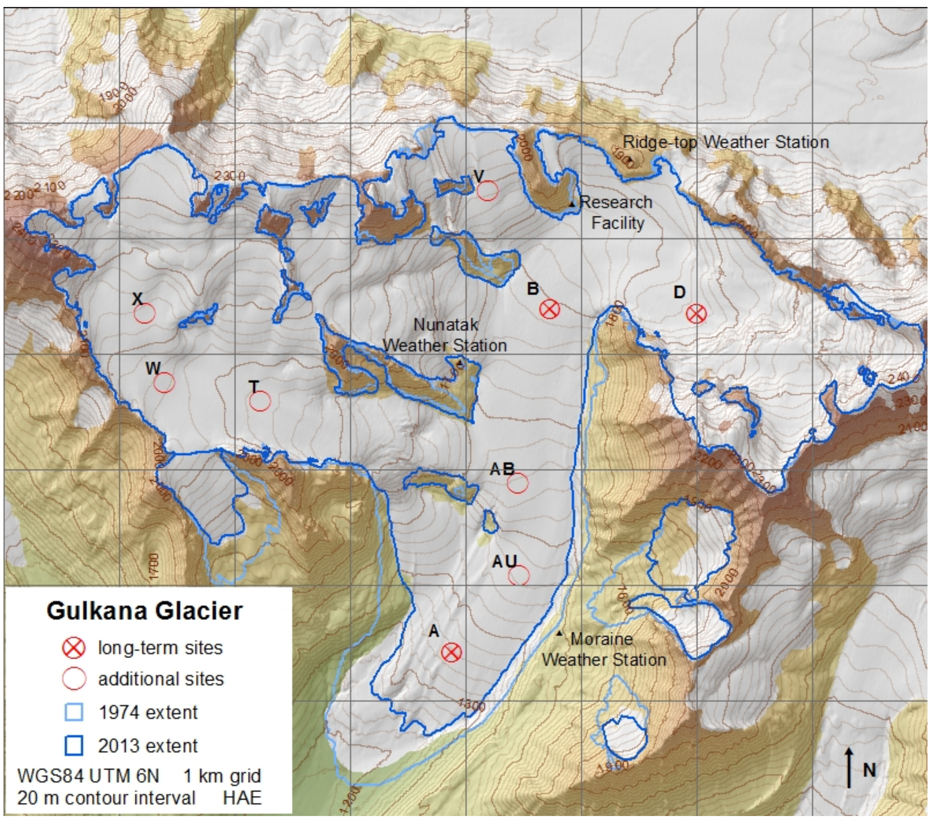

Figure 2. Map of Gulkana Glacier showing location of mass balance stake sites.

Site	Easting [m]	Northing [m]
A	578884.3	7015423
AU	579462	7016084
B	579727	7018389
C	579152	7019865
D	580997	7018351

la	578652	7014933
ab	579446	7016882
t	577224	7017591
v	579187	7019406
w	576386	7017751
x	576223	7018354

Table 2. Index stake sites at Gulkana Glacier, corresponding to locations shown in Figure 1. Rows with capital letters as labels indicate primary long term sites, and lower-case labels indicate secondary and/or shorter-term sites. Site AU replaced site A in 2012 when it became inaccessible due to terminus retreat. Site D replaced site C in 1975 as a more representative accumulation area site. Overlapping measurements occurred only in 1975.

Input data

In the files that are described below. In all file names, *glacier* may be replaced with either Wolverine or Gulkana. NaN indicates the lack of a measurement or an unresolved value. A value of 0 means the measured value is 0.

1. Time series of point water balances measurements. File: *glacier*_mb_input.txt with columns as described below.

    - **Balance year:** USGS uses the floating date time system, in which the balance year refers to the time span equal or approximately equal in duration to one calendar year to which the annual mass balance applies.
    - **Site name:** See figure 1 for location of index sites on the glacier. Table 1 provides the coordinates for these sites.
    - **Date 1**: Date of spring measurement
    - **Date 2**: date of fall measurement
    - **Z**: Elevation [m] of the measurement site.
    - **Winter**: winter balance at the site estimated from stake, pit, core, and/or probe measurements provided in units of [m w.e.] Summer balances may be derived as the difference between Annual and winter mass balance. Values provided in this file may represent an average of multiple measurements made during field visits.
    - **Annual**: Annual (net) balance at the site estimated from stake and/or pit measurements provided in units of [m w.e.] Summer balances may be derived as the difference between Annual and winter mass balance. Values provided in this file may represent an average of multiple measurements made during field visits.
    - **Winter ablation**: Ablation [m w.e.] that occurred after the fall field visit, and was measured the subsequent spring visit. Although measured in balance year i+1 this ablation occurred in balance year i. We partition the balance in this way to be clear about the timing of the measurements. Depending how the user wishes to analyze the data winter ablation may be excluded if desired.
    - **Summer accumulation:** Accumulation [m w.e.] that occurred before the fall field visit, but was measured at the time of the fall visit. Although measured in balance year I this accumulation may better apply to balance year i+ 1. We partition the

balance in this way to be clear about the timing of the measurements. Depending how the user wishes to analyze the data winter ablation may be excluded if desired.

Uncertainties: For all input values, uncertainties are poorly constrained, and evaluated primarily on the basis of expert opinion.

- *Time*: time is constrained to days.
- *Snow accumulation*: Primary sources of uncertainty exist from surface roughness, snow density variability, stake deformation and drilling and discrepancies between various types of observations (probe depths, stake length change and snow pit depth). Nominal uncertainty from these sources has been previously estimated to range between 15-20% (Dunse and others, 2008; Heinrichs and others, 1995).
- *Snow and ice melt*: Primary sources of uncertainty exist from surface roughness, snow density variability, stake deformation and drilling and discrepancies between various types of observations (probe depths, stake length change and snow pit depth). Nominal uncertainty from these sources is estimated at 0.10 m w.e. (Heinrichs and others, 1995).
- *Temperature*: Measurement uncertainty has decreased in time with sensor evolution. Through 1998, average daily temperatures were recorded using analog instruments with uncertainties estimated of ± 1 °C. After 1998, digital sensors with shorter response times and measurement intervals have decreased this uncertainty to ± 0.25 °C. (Kennedy and others, 1997).
- *Precipitation*: Uncertainty in precipitation catch is hard to estimate, but are dominated by thermal expansion during the analog record (all data provided here). Moreover, catch ratios are known to decrease substantially in winter, especially during snow events with wind. Daily uncertainties for these gages were estimated to be 5-8 mm (Kennedy, 1995).

2. Time dependent glacier geometry is provided as an Accumulation Area Distribution (AAD) in the file *glacier*_AAD.txt. Columns represent area in 100 m elevation bins, and the area in each bin is given in km^2. The first row specifies the median elevation for the bin. The first column gives the balance year that the areas represent. The total glacier area can be calculated by summing across the row for any given year. Wolverine Glacier areas are derived from DEMs constructed in 1979, 1995, 1998, 2002 and 2008 and area is interpolated linearly between DEM acquisitions. Gulkana Glacier areas are derived from DEMs constructed in 1974, 1993, 1999, 2007, 2009 and 2010, and area is interpolated linearly between DEM acquisitions.
3. Weather data is provided in the files *glacier*_dailyprecip.txt and *glacier*_dailytemp.txt, which have identical format. Column one provides the date in [yyyy/mm/dd] format and column two provides the meteorological observation. Precipitation is given in [mm w.e.] and temperature in [°C]. Precipitation values represent daily totals and temperature values represent daily averages.

   Original gauges were designed for deployment in high-precipitation regions, and functioned by recording the stage of a large storage reservoir (e.g., Kennedy and others, 1997). At Wolverine, the original precipitation gauge was removed 2 September 2015. Data since then is from a load sensor gauge that was installed during September, 2011. The original gauge was removed from Gulkana Glacier on 23 September 2015. After this date, data is obtained from a load-sensing gauge that was installed during April, 2012. The first year of operations for these gauges was sub-optimal, but a minimum of one year of robust overlap was obtained. Precipitation catch improved with the new gauges. Data from the periods of overlap is available upon request.

Site	Easting [m]	Northing [m]	Elevation [m]
Wolverine Glacier	393070	6695520	990
Gulkana Glacier	579800	7015700	1480

Table 3. Location of weather stations.

To produce glacier-wide mass balance solutions, these weather data are used to solve for the timing of mass extrema. The USGS uses data from Seward AK to fill data gaps in the Wolverine glacier meteorology record (van Beusekom and others, 2010). In Weather station data from Trims Camp AK (1964-1979) and Paxson AK (1979-present) is used to fill gaps in the Gulkana glacier record.

Output

1. Glacier-wide mass balance estimated only using field observations are provided in the files *glacier*_Output_annual.txt and *glacier*_Output_seasonal.txt. These results are produced using the 'index method' (van Beusekom and others, 2010) where the glacier area is partitioned into three zones such that the long-term measurement site is located at the median elevation of each zone. The column format of the output files is as follows:

   Annual

   - **Date of mass minimum**: USGS uses the floating date time system, in which the balance year refers to the time span equal or approximately equal in duration to one calendar year to which the annual mass balance applies. The dates here are the solved estimate for the day of the mass minimum, but the year can be used as a stand-alone representative for the balance year.
   - **B_a:** Glacier-wide average annual mass balance
   - **B_cum**: Glacier-wide average cumulative mass balance

   Seasonal

   - **Date**: Date of glacier-wide mass extrema, solved for with a degree-day model
   - **B_seas**: Change in glacier mass balance since the previous observation. These values are equivalent to summer and winter mass balances.
   - **B_cum**: Glacier-wide average cumulative mass balance on seasonal time steps

2. Both annual and seasonally time-stepped glacier-wide mass balance calibrated with geodetic observations (O'Neel and others, 2014) are provided in the files *glacier*_CalibratedOutput_*annual/seasonal*.txt. USGS follows much of the re-analysis

procedure outlined by Zemp and others, (2013), however, we use a single, weighted least-squares fit between the geodetic mass balance time series and the glaciological time series. The calibration coefficient for Wolverine Glacier is -0.4481 m a^{-1} and for Gulkana Glacier is +0.0276 m a^{-1}. The calibrations are applied annually, distributing the correction linearly throughout the year as determined by the solution for the date of minimum and maxim mass. As a result, the winter balance receives a heavier weight than does the summer balance. Data pertaining to the geodetic calibration will be released in Phase 2 of this project. Files are formatted identically as the non-calibrated output but have a naming structure indicating a geodetic calibration has been applied.

Uncertainties: Extrapolation and interpolation errors present in the glacier-wide average mass balance solutions here are difficult to quantify. Earlier error estimates suggest values of 0.2 m w.e. are appropriate (van Beusekom and others, 2010).

References

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