# Glacier-Wide Mass Balance and Compiled Data Inputs

Last Revision: ver 8.1, February 2024

**Overview:** This document describes the data associated with the long-term mass balance measurement campaigns at the USGS Benchmark Glaciers, including Gulkana, Wolverine, Lemon Creek, South Cascade and Sperry glaciers. The data descriptions outlined in this document are also relevant to Taku Glacier data, unless otherwise noted.

## SUMMARY

Since the late 1950s, the USGS has maintained a long-term glacier mass-balance program at three North American glaciers. Measurements began on South Cascade Glacier, WA in 1958, expanding to Gulkana and Wolverine glaciers, AK in 1966, and later Sperry Glacier, MT in 2005. The Juneau Icefield Research Program has measured surface mass balance on Lemon Creek and Taku Glacier since the mid-1940s, with USGS providing complimentary seasonal measurements of Lemon Creek beginning in 2014 (JIRP; Pelto and others, 2013). Direct field measurements of point glaciological data are combined with weather and geodetic data 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 (O'Neel and others, 2019; prior to v 3.0 van Beusekom and others, 2010) 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.

This portion of the data release includes glacier wide mass balance, as well as the refined inputs used in these calculations. Input data are of three types: 1) time-variable area altitude distribution (AAD); 2) time series of point water balance at long term sites (with secondary sites given in recent years); 3) weather data from nearby stations, either installed along the glacier margins or taken from a nearby site if continuous glacier-adjacent data is unavailable. The USGS runs a coded analysis to transform the three input data types to the output glacier-wide data. Output data represent surface mass balance estimates. The output solution is a geodetically calibrated, conventional glacier-wide mass balance, which represents our preferred solution. Conventional glacier-wide mass balance from direct observations without calibration can be easily derived by using the geodetic calibration coefficients provided, if desired. We do not explicitly 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 raw point measurements and other mass-balance related data are included in the larger USGS Benchmark Glacier Project Comprehensive Data Collection, available at https://doi.org/10.5066/P9AGXQSR.

Preliminary mass balance estimates for the current calendar year are provided, but do not include direct measurements of ablation after the date of the fall visit. Preliminary estimates of mass balance model this winter ablation for the current year. During subsequent field visits in the following calendar year, any ablation that occurred over the winter season is measured and used to revise the previously modeled estimate of mass balance.

## PURPOSE

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

## PROJECTION AND DATUM:

All maps and coordinates provided are referenced to the Universal Transverse Mercator (UTM) coordinate system. Gulkana and Wolverine glaciers are located in UTM zone 6N (EPSG 26906), Lemon Creek and Taku Glaciers are in UTM Zone 8N (EPSG 26908), South Cascade Glacier is located in UTM zone 10N (EPSG 26910), and Sperry Glacier is located in UTM zone 12N (EPSG 26912). Elevations are referenced to the WGS84 ellipsoid.

## 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: 1 m w.e. = 1000 kg $m^{-2}/\rho_W$ (Cogley and others, 2011).

## SITES

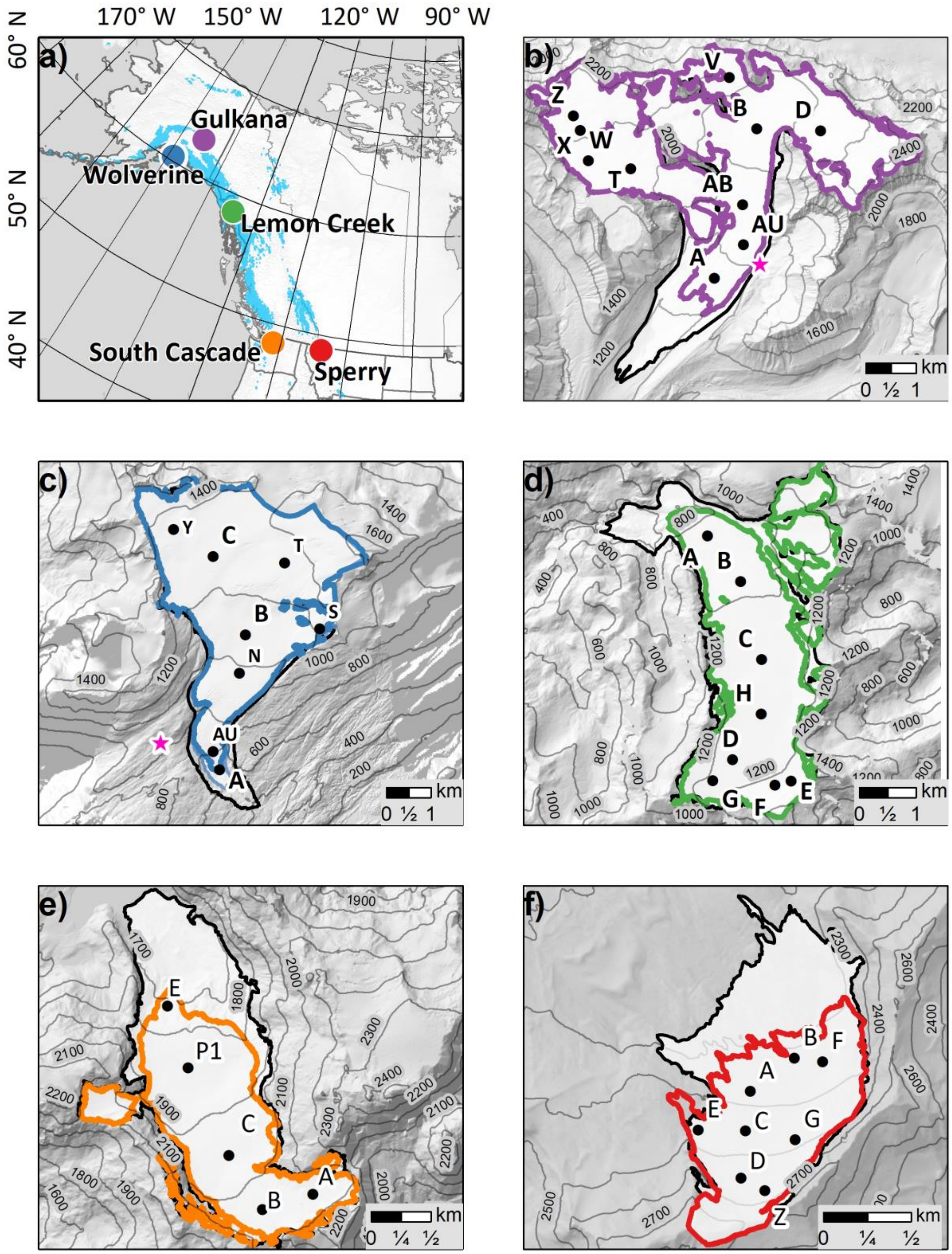


**Figure 1:** Glaciers in the USGS Benchmark Glacier Program. Figure 1: (a) USGS Benchmark Glacier locations at continental scale with North American glacier extent from Global Land Ice Measurements from Space database (GLMIS) shown in cyan [GLIMS and NSIDC 2005, updated 2018]. The five benchmark glaciers are shown as colored dots (b-f). Individual glacier map panels of Gulkana (b), Wolverine (c), Lemon Creek (d), South Cascade (e), and Sperry glaciers (f) show the modern glacier outline in a color corresponding to the glacier in panel a, and mid-century (1948 to 1958) glacier extent in black. Mass balance measurement sites are labeled with site names and black dots. Glacier-adjacent weather stations used for climate forcing in mass balance modeling are shown with a pink star at Wolverine and Gulkana glaciers. Weather stations used for mass balance calculations at the remaining glaciers are outside of the map panels, and are not shown. Data from Taku Glacier is not shown in this figure.

## INPUT DATA

In the file names described below, *glacier* may be replaced with the benchmark glacier name (e.g. Sperry or Gulkana). NaN indicates the lack of a measurement or an unresolved value. A value of 0 means a measured zero.

1. Time series of point water balances measurements is provided in the file Input_*Glacier*_Glaciological_Data.csv with columns as described below.

   - **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.
   - **Spring_date**: Date of spring measurement
   - **Fall_date** Date of fall measurement
   - **Z**: Elevation (m) of the measurement site above sea level.
   - **bw**: Winter balance at the site estimated from stake, pit, core, and/or probe measurements provided in units of m w.e.. Values provided in this file may represent an average of multiple measurements made during field visits.
   - **ba**: 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. At Sperry Glacier, annual is derived as the sum of winter and summer mass balance. These two methods are arithmetically equivalent. 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. In the case where winter ablation was not measured on the spring field visit in year i+1, and new snow was not present on top of the summer surface in the fall field visit of balance year i, winter ablation is represented as 'nan'
   - **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 applies to balance year i+ 1. We partition the balance in this way to be clear about the timing of the measurements. Thus depending how the user wishes to analyze the data, summer accumulation may be excluded if desired. If no data available, represented as 'nan'.

   *Uncertainties:* For all input values, uncertainties are poorly constrained, and evaluated primarily on the basis of expert opinion. Uncertainty sources and magnitudes are cited accordingly.

   - *Time*: Time uncertainty is defined on the order of days.
   - *Snow accumulation*: Measurement uncertainty is primarily due to surface roughness, snow density variability, stake deformation and drilling, and discrepancies between various types of observations (probe depths, stake length change, and snow pit depths). Nominal uncertainty from these sources has been previously estimated to be 0.3 m w.e. (Beedle and others, 2014; Huss and others, 2009).
   - *Snow and ice melt*: Measurement uncertainty is primarily due to surface roughness, snow density variability, stake deformation and drilling, and discrepancies between various types of observations (probe depths, stake length change, and snow pit depths). Nominal uncertainty from these sources is estimated to be 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 decreased measurement uncertainty to ± 0.25 °C (Kennedy and others, 1997).

- *Precipitation*: Precipitation catch error is difficult to estimate, but measurement uncertainty is dominated by thermal expansion during the analog record prior to the mid-1990s. Moreover, catch ratios are known to decrease substantially in winter, especially during snow events with wind. Daily uncertainty is estimated to be 5-8 mm (Kennedy, 1995).

2. Time dependent glacier geometry is provided as an Area Altitude Distribution (AAD) in the file Input_*Glacier*_Area_Altitude_Distribution.csv. Columns represent area in 100 m elevation bins, except Sperry Glacier which uses 30 m bins, and South Cascade Glacier which uses 50 m bins. The area in each bin is given in $km^2$. The first row is a column header, and 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. Glacier areas are derived from digital elevation models (DEMS) constructed in a number of years, and area is interpolated linearly between DEM acquisitions.

3. Dates of DEMs used to construct the AAD for each glacier, along with uncertainty for each date, is given in the file Input_*Glacier*_Geodetics.csv.

    - **Date:** Date of DEM acquisition. Date of the reference DEM is identifiable by the 0.00 m w.e. entry for Mass_Change_mwe.
    - **Mass_Change:** Geodetic mass balance for the time interval between the Date of DEM acquisition and the Date of the reference DEM. Geodetic mass balance is computed by differencing digital elevation models to calculate glacier volume change and then converting volume to mass using the 850+/-60 kg $m^{-3}$ material density assumption described by Huss (2013). Note that starting with version 8.0 this m w.e. geodetic mass change result reflects time-varying glacier area, i.e., the glacier area assignment is not fixed but uses the average glacier area over the geodetic interval. Details found in O'Neel et, al (2019) and Florentine et al. (in press). Units are meters of water equivalent.
    - **Uncertainty:** Uncertainty (m w.e.) due to error associated with the elevation data (DEM) differencing required to compute glacier volume change, and the material density assumption required to convert ice volume change to water equivalent mass (Huss, 2013). Quantification of geodetic mass balance uncertainty is described fully in O'Neel and others (2019).

4. Weather data is provided in the file Input_*Glacier*_Daily_Weather.csv. Date is given in yyyy/mm/dd format, and the remaining three columns provide meteorological observation and weather station elevation. Precipitation is given in mm w.e. and temperature in °C. Precipitation values represent daily totals and temperature values represent daily averages of all temperatures recorded. Elevation is given in m.

    Detailed information on specific stations, and sub-daily data beginning in the 1990s at the analog-digital transition is available in an associated weather data release, available under the USGS Benchmark Glacier Mass Balance and Project Data collection via https://doi.org/10.5066/F7BG2N8R.

    In glacier-wide analyses, meteorological stations installed within the glacier watershed are used at Wolverine and Gulkana glaciers. Discontinuous local records for South Cascade Glacier, Lemon Creek Glacier, and Sperry Glacier prompted use of continuously operating area weather stations. Portions of this discontinuous, local station data is available in the associated weather data release. Locations of weather stations used for calculation of glacier-wide mass balance are given below.

| Glacier | Approximate Elevation (m) | Location | Latitude | Longitude |
|---|---|---|---|---|
| Gulkana | 1480 | Moraine | 63.2614 | -145.4102 |
| Wolverine | 990 | Adjacent Slope | 60.3819 | -148.9397 |
| Lemon Creek | 5 | Juneau Airport | 58.3566 | -134.5640 |
| Taku | 5 | Juneau Airport | 58.3566 | -134.5640 |
| South Cascade | 270 | Diablo Dam | 48.7141 | -121.1430 |
| Sperry | 1920 | Flattop SNOTEL | 48.8017 | -113.8570 |

**Table 1:** Location of primary weather station used for each glacier. Gulkana and Wolverine are within the glacier basin; others are continuously operating weather stations in the area of the glacier. Coordinates are given in decimal degrees; elevations are in meters.

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). Gaps in the Gulkana record are filled with data from the Gulkana Airport in Glenallen, AK. In Montana, near Sperry Glacier, data gaps from the Flattop SNOTEL are filled with data from the Hungry Horse Dam. Timeseries from the Juneau Airport for Lemon Creek and Taku, and Diablo Dam for South Cascade are not filled with data from a secondary site. Prior to Version 5.0, a lapse rate of -6.5 C/km was used to calculate on-glacier temperatures across at all Benchmark Glaciers. In Version 5.0 forward, using local weather stations the Lemon Creek Glacier lapse rate was optimized, resulting in a -5.0 C/km lapse rate as detailed in McNeil et. al 2020, "Explaining mass balance and retreat dichotomies at Taku and Lemon Creek Glaciers, Alaska". Mass balance estimates rely on the relationship between winter precipitation observed at a weather station, and snow/ice observed on the ground during spring mass balance measurements and the balance profile. Additional years of data allow for further refinement of this relationship, which changes the historical timeseries very slightly.

5. Index site locations are given in the file *Glacier*_UTM*Zone*.csv. Coordinates are given in UTM (WGS84), in the zone appropriate for each location. Gulkana and Wolverine glaciers are located in UTM zone 6N (EPSG 26906), Lemon Creek Glacier is in UTM Zone 8N (EPSG 26908), South Cascade Glacier is located in UTM zone 10N (EPSG 26910), and Sperry Glacier is located in UTM zone 12N (EPSG 26912). At South Cascade Glacier, stake locations have not been consistent over the period of record; approximately 100 m of drift should be assumed for each site. File naming convention: [GLACIER]_UTM[zone]: where [GLACIER] = glacier name, [zone] = UTM zone. Within the file, the column "Site" denotes a unique identifier of each mass balance measurement site on a given glacier. Sites have specific geographic coordinates for sampling across years. Corresponds to the "site_name" variable in other tables included in this data package. Maps of all sites are provided in the README and site coordinates are provided in the table "[GLACIER]_UTM[zone].csv" included in this data package.

6. Where available, sub-seasonal glaciological measurements are given in the file Input_*Glacier*_SubSeasonal_Glaciological_Data.csv. These measurements are taken opportunistically, and are not available for all Benchmark Glaciers. Where available, they are used to better constrain the mass balance calibration. Further details are available in supplemental materials of O'Neel and others (2019). Note that sub-seasonal data is not provided for all glaciers in this data release. File naming convention: Input_[GLACIER]_SubSeasonal_Glaciological_Data: where [GLACIER] = glacier name

   - **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:** Unique identifier of each mass balance measurement site on each glacier. Sites have specific geographic coordinates for sampling across years. Corresponds to the "site_name" variable

in other tables included in this data package. Maps of all sites are provided in the README and site coordinates are provided in the table "[GLACIER]_UTM[zone].csv" included in this data package.

- **Date1:** Date of first observation
- **Date2:** Date of second observation
- **Elevation:** Elevation as taken from a digital elevation model (DEM) in the year of observation, given in meters above sea level.
- **Surface1:** Material on surface at time of Date1 observation
- **Surface2:** Material on surface at time of Date2 observation
- **db:** Change in mass balance between Date1 and Date2, in m. w.e.

7. Transient snow line data are given in the file Input_*Glacier*_TSL_Date.csv. Date is given in yyyy/mm/dd format, and elevation is given in meters above sea level. Currently, this is available only for Lemon Creek Glacier, and is necessary there due to the mid-summer timing of glaciological measurements there prior to 2016. Snow line elevation is determined visually on the centerline of the glacier in satellite imagery, primarily Landsat, with the addition of some Sentinel and Worldview images in more recent years.

## OUTPUT

Both annual and seasonally time-stepped glacier-wide mass balance solutions calibrated with geodetic observations (O'Neel and others, 2014) are provided in files with the naming convention of Output_*Glacier*_Glacier_Wide_solutions_calibrated.csv. These results are produced using a two-piece linear balance profile based on elevation. This two-piece balance profile was chosen because it incorporates physical expectations of variable melt rates for snow and ice. Our choice was guided by several factors including: 1) feasibility and goodness-of-fit at all glaciers, 2) applicability for both sparse and robust data sets, and 3) capacity to include short-lived expanded stake and ground-penetrating radar campaigns above long-term index sites. Each fit is constrained to have a single interior breakpoint, or knot, in the piecewise-linear fit. Further details are given in O'Neel and others, 2019.

Prior to version 3.0 of this data release, values were calculated using the "index method" (van Beusekom and others, 2010). Version 3.0 of this data release results from a significant reanalysis effort, detailed in O'Neel and others, 2019. File naming convention: Output_[GLACIER]_Glacier_Wide_solutions_calibrated: where [GLACIER] = glacier name

### Calibration

USGS follows much of the re-analysis procedure outlined by Zemp and others (2013). However, for geodetic calibration, we adopt a piecewise/ breakpoint fitting approach over approximately decadal intervals. This maximizes the incorporation of geodetic data, while minimizing the impacts of non-stationarity that manifest in multi-decadal calibrations, and limits the impact of errors arising from material density assumptions. Note that starting with version 8.0 this m w.e. geodetic mass change result reflect time-varying glacier area, i.e., the glacier area assignment is not fixed but uses the average glacier area over the geodetic interval. For further details, see O'Neel (2019) and Florentine et al. (in press). Associated geodetic data used to derive the calibrations are given in an accompanying data release, found under the USGS Benchmark Glacier Mass Balance and Project Data collection via https://doi.org/10.5066/F7BG2N8R.

The columns in the output file contain the following:

- **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
- **Ba_Date**: 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, using local precipitation, temperature data, and a degree day model.
- **Bw_Date**: Date of mass maximum. Solved estimate for the day of mass maximum, using local precipitation, temperature data, and a degree day model.
- **Ba:** Glacier-wide average annual mass balance, in m w. e.
- **Bs:** Glacier-wide summer mass balance, in m w.e.
- **Bw:** Glacier-wide winter mass balance, in m w.e.
- **ELA:** Equilibrium line altitude, as solved during the calculation of glacier-wide mass balance, in meters above sea level
- **Calibration:** geodetic calibration, given in units of m. w.e. If an uncalibrated, conventional glacier-wide mass balance is desired, it can be calculated easily using the given calibration. For annual balance, the calibration is simply added to the value in Ba. For summer (Bs) and winter (Bw) balances, half the calibration should be added to each.

## SUGGESTED CITATION:

Where possible, please cite larger mass balance project data collection, of which this release is a part:

U.S. Geological Survey Benchmark Glacier Program, 2020, USGS benchmark glacier project comprehensive data collection: U.S. Geological Survey data release, https://doi.org/10.5066/P9AGXQSR.

This dataset can be cited separately, if needed, as:

U.S. Geological Survey Benchmark Glacier Program, 2016, Glacier-Wide Mass Balance and Compiled Data Inputs: USGS Benchmark Glaciers (ver. 8.0, November, 2023 ): U.S. Geological Survey data release, https://doi.org/10.5066/F7HD7SRF

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