Glacier-Wide Mass Balance and Compiled Data Inputs: Juneau Icefield Glaciers

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Overview: This document describes the data associated with the long-term mass balance measurement campaigns at select Juneau Icefield glaciers.

SUMMARY

Since the 1940s, the Juneau Icefield Research Program (JIRP) has been measuring surface mass balance on the Juneau Icefield, while also providing expeditionary training to high school, undergraduate, and graduate students. This is the longest ongoing program of its kind in North America. The program nominally occurs between late June and late August, traversing between Juneau, Alaska and Atlin, British Columbia. JIRP has examined the surface mass balance of the Juneau Icefield since 1946, with principal efforts focused on Lemon Creek Glacier and Taku Glacier. Glaciological, geodetic, and meteorological data have been collected by JIRP to characterize the interaction between the climate and glaciers of the Juneau Icefied. 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 basic analysis framework (O'Neel, 2019, in prep; McNeil et. al, 2019) is the same at each glacier to enable cross-comparison between output time series. However, in this data release for Taku and Lemon Creek glaciers temperature lapse rates are optimized using on-icefield weather data. This changes the degree day factor in the melt model, giving small post-geodetic calibration differences on the order of 2-3 cm. Details are described in McNeil (2019). Vocabulary used follows Cogley and others (2011) Glossary of Glacier Mass Balance.

This portion of the data release includes glacier wide mass balance solutions for Taku and Lemon Creek Glaciers, as well as the refined inputs used in these calculations. Input data are of three types: 1) time-variable area altitude distribution; 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.

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. Lemon Creek and Taku Glaciers are in UTM Zone 8N (EPSG 26908). 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}/ρ_W (Cogley and others, 2011).

INPUT DATA

In the file names described below, *glacier* may be replaced with the glacier name (e.g. Taku or Lemon Creek). 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 applies to balance year i. We partition the balance in this way to be clear about the timing of the measurements. Thus depending on how the user wishes to analyze the data, winter ablation may be excluded if desired. If no data available, 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 $\pm$ 1 °C. After 1998, digital sensors with shorter response times and measurement intervals decreased measurement uncertainty to $\pm$ 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 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.
    - **Surface_Elevation_Change:** Difference of surface height (m) relative to the master DEM, which is the final, most recent DEM in the series. Details found in O'Neel et, al (2019). Units are meters of height change, not meters of water equivalent.
    - **Uncertainty:** Stochastic error related to elevation differencing, including components accounting for coregistration alignment, interpolation, and total mass balance error. This is a sophisticated approach, and is described fully in O'Neel (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 two columns provide meteorological observation. Precipitation is given in mm w.e. snd temperature in °C. Precipitation values represent daily totals and temperature values represent daily averages of all temperatures recorded.

    A lack of precipitation data, in combination with a somewhat incomplete record of temperature, prompted use of continuously-operating area weather stations over local icefield meteorological data. 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; the same site is used for both Lemon Creek and Taku glaciers.

Glacier	Approximate Elevation (m)	Location	Latitude	Longitude
Lemon Creek	5	Juneau Airport	58.3566	-134.5640
Taku	5	Juneau Airport	58.3566	-134.5640

    Table 1: Location of primary weather station used for each 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. Timeseries from the Juneau Airport are nearly continuous, and there is no need to fill gaps with data from a secondary site.

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. For Juneau Icefield glaciers, this is UTM Zone 8N (EPSG 26908). In the early portion of the record on the Juneau Icefield stake locations were not entirely consistent; approximately 100 m of drift should be assumed for each site.

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 locations. 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).

    - **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.
    - **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 the mass balance profile method (Fountain & Vecchia, 1999; Beedle and others, 2014; Cogley and others, 2011). 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 a forthcoming publication (O'Neel and others, 2019).

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. For further details, see O'Neel (2019).

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 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 (Ba) and winter (Bw) balances, half the calibration should be added to each.

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).

SUGGESTED CITATION:

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