Explaining mass balance and retreat dichotomies at Taku and Lemon Creek Glaciers, Alaska

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**Supplementary Material**

**S-1 Previous Studies**

The Juneau Icefield Research Program (JIRP) has produced a wealth of mass balance related products and publications for the Juneau Icefield since the mid-1940s (e.g., Field and Miller, 1950; LaChapelle, 1954; LaChapelle, 1955; Nielson, 1957; Wilson, 1959; Miller, 1963; Heusser and Marcus, 1964a; Heusser and Marcus, 1964b; Miller, 1975; Pelto and Miller, 1990; Marcus and others, 1995; Miller and Pelto, 1999; Pelto and others, 2008; Pelto, 2011; Pelto and others, 2013). However, additional organizations, such as the University of Alaska Fairbanks, University of Alaska Southeast, and the US Geological Survey (USGS) have also contributed substantially during the past two decades (e.g., Nolan and others, 1995; Post and Motyka, 1995; Motyka and Beget, 1996; Sapiano and others, 1998; Motyka and Echelmeyer, 2003; Arendt and others, 2006; Kuriger and others, 2006; Larsen and others, 2007; Truffer and others, 2009; Melkonian and others, 2014; Kienholz and others, 2015; Larsen and others, 2015; Berthier and others, 2018; Roth and others, 2018).

 All glaciological measurements from both Taku and Lemon Creek Glaciers were used in our analysis, including additional data not collected by JIRP. **Fig. S1.** Displays the location of additional ablation measurements measured during 2003­–05 by the University of Alaska (UA) in (**Fig. 1a.**), the US Geological Survey (USGS) and UA at Taku Glacier during 2013–2015 (**Fig. 1b**.) and the USGS at Lemon Creek Glacier since 2016 (**Fig. 1c.**). **Fig. S2.** Shows the distribution of glaciological data collected by JIRP, UA, and the USGS with respect to time.

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**Fig. S1.** Location of non-JIRP glaciological measurements at Taku Glacier (a and b) and Lemon Creek Glacier (c). (a) Ablation wires measured by the University of Alaska in 2004–05. (b) Seasonal and annual mass balances measured by the USGS and University of Alaska in 2014–15. (c) Seasonal and annual mass balances measured by the USGS in 2016–18.



**Fig. S2.** The distribution of glaciological data collected by JIRP (blue), USGS (red), and University of Alaska (grey) with respect of time and elevation during the 1946–­2018 period. (a) Digitized ablation data, (b) snow pit measurements and (c) transient snowline observations for Taku Glacier. (d, e and f) Same plots but for Lemon Creek Glaciers.

**Table S1** lists previous geodetic studies spanning the 1948–2016 interval. Estimates of area and/or mass change rates are highly variable, potentially due to different analysis approaches and study intervals.

**Table S1.** Geodetic studies of Taku (TG) and Lemon Creek glacier (LCG). For each study the analysis used are listed as Photogrammetry (PG), Topographic Maps (TM), Laser altimetry (LA), Synthetic Aperture Radar (SAR), Moraine Mapping (MM), Ground Penetrating Radar (GPR) and Flow Velocity Fields (FVF).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Year(s) | Glacier(s) | Study | Focus | Analysis |
| 1948;57 | LCG | Heusser and Marcus, 1964b | Area and mass change | PG |
| 1946–86 | TG | Pelto and Miller, 1990 | Area | TM |
| 1957–89 | LCG | Marcus and others, 1995 | Area and mass change | PG |
| 1750–1989 | TG | Post and Motyka, 1995 | Terminus change | MM and PG |
| 1750–1989 | TG | Motyka and Post, 1995 |  Terminus change | MM and PG |
| 1750–1993 | TG | Motyka and Bedget, 1996 | Terminus change | MM and PG |
| 1957–95 | LCG | Sapiano and others, 1998 | Mass change | TM and LA |
| 1948–93 | TK; LCG | Arendt and others, 2006 | Mass change | TM and LA |
| 1890–03 | TK | Motyka and others, 2006 | Terminus change | PG and GPR |
| 1948–00 | TK | Larsen and others, 2007 | Mass Change | TM and SAR |
| 2000–10 | TK | Melkonian and others, 2014 | Mass Change |  SAR and PG |
| 2013 | TK; LCG | Keinholz and others, 2015 | Area | FVF |
| 1993–12 | TK; LCG | Larsen and others, 2015 | Mass Change | LA |
| 2000–16 | TK; LCG | Berthier and others, 2018 | Mass Change | PG |

**S-2 SRTM Snow Penetration Assumptions**

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**Fig. S3.** Glacier-wide snow depths (gray) approximated using the mass balance model (**Section 4.2.2**) at (a) Taku and (b) Lemon Creek glaciers, between the ca. 1999 mass minimum date and 11 February 2000. Snow depths were converted from w.e. units using assumed densities between 400 and 500 kg m­−3. Snow penetration rates of 4 ±2 m (solid black line ± dashed black line) as concluded by Rignot and others (2001) is presented as comparison to our modeled glacier-wide snow accumulation.

**S-3 DEM interpolation**

Unresolved areas within the 1979 and 1989 Lemon Creek Glacier DEMs (**Table 1**) were interpolated using the function of elevation change in respect to the reference DEM’s elevation. Elevation change was binned and averaged at 50 m intervals along the glacier’s elevation range. A linear spline, fit to the average elevation change in respect to elevation within each bin, was then used to interpolate missing elevation change values in each DEM (Larsen and others, 2015; **Fig. S4**).



**Fig. S4.** Example of the elevation change function used to infill DEM holes. Grey dots represent observed rates of elevation change, the orange line represents the mean elevation change as a function of elevation and error bars show the MAE within each 50 m elevation bin.

**S–4 Comparison to Previous Geodetic Studies**

Our area assessments (**Table 2**) were significantly different (>2%; **Section 4.1.3**) from those previously published for Taku Glacier; conversely, overall agreement was found at Lemon Creek Glacier. These differences at Taku Glacier primarily occurred along the glacier’s nine ice divides, where boundaries were previously hand drawn. This resulted in a 7% (~50 km2) difference in area compared to previous assessments (e.g., Pelto and others, 2013; Pfeffer and others, 2014; RGI Version 3). The RGI version 4 (Kienholz and others, 2015; RGIv4) compared considerably better (2%), due to their incorporation of flow velocity fields (same as used in this study; Burgess and others, 2013). A 1% (~7 km2) difference from RGIv4 exists along ice divides delineations of Taku Glacier. An additional 1% difference resulted from minor discrepancies in the ablation zone, due to the inclusion of exclusion of adjacent ice bodies.

Differences in our area assessments from many of those previously published for Lemon Creek Glacier (Heusser and Marcus, 1964a; Marcus and others 1995), were not significantly different (**Section 4.1.3**), ranging from <1 to 2% (~0.25 km2). However, the exclusion of disconnected tributary slopes (**Section 5.1**), in RGIv4, produced a substantial difference (10%; ~1.5 km2). This highlights the importance of consistent area delineation when quantifying glacier area change.

Our geodetic mass balances (**Table 5)** agreed well with most previously published geodetic mass balances **(Table S2**). What differences did exist likely resulted from variations in co-registration methods, acquisition date, or data quality. For example, Larsen and others (2007) applied image warping software to align DEMs, where Arendt (2006) used no co-registration method, compared to our analysis which used co-registration methods described by Nuth and Kääb (2011). The disagreement between our work and these studies is less than the vertical uncertainty of the 1948 NED DEM (**Table S2)**.

Our geodetic mass balances compared poorly with those by Melkonian and others (2014), confirming previous studies (Berthier and others, 2018). These two recent studies (Melkonian and others ,2014; Berthier and others, 2018) used ASTER DEMs analyzed with a pixel-by-pixel regression method (Brun and others, 2017). The footprint of ASTER DEMs does not cover the extent of larger glaciers (e.g. Taku Glacier), prohibiting assessment of glacier-wide surface elevation changes between discrete dates. Moreover, the low resolution of ASTER imagery often results in unresolved areas in the accumulation zone (Berthier and others, 2018). Finally, acquisition dates of DEMs vary considerably (Melkonian and others, 2014), incorporating seasonal mass change into these of analyses.

Snow penetration within the SRTM DEM was suggested (Berthier and others, 2018) to have positively biased mass balances derived by Melkonian and others (2014). However, our average mass balances (including SRTM) were more negative than either of these studies. We suggest the significant difference results from data coverage variability, imagery acquisition dates, co-registration methods, and resampling methods used by Melkonian and others (2014) ­­­­­not the use of SRTM. Furthermore, we note the pixel-to-pixel regressions in Fig. 4 of Melkonian and others (2014) show good agreement with trends derived from 10–20 additional data points and SRTM.

 **Table S2.** Comparison of previous mean mass balances to those from this study.

|  |
| --- |
| Taku Glacier  |
| Period (yyyy–yy) | Previous (m w.e. a−1) | This study (m w.e. a−1) | Source |
| 1948–93 | 0.59 | 0.55 | Arendt, 2006 |
| 1948–99 | 0.39 | 0.45 | Larsen et al., 2007 |
| 1993–97 | −0.24 | −0.49 | Arendt, 2006 |
| 1993–12 | 0.13 | −0.09 | Larsen et al., 2015 |
| 2000–10 | 0.44 | 0.03 | Melkonian et al., 2014 |
| 2000–16 | −0.01 | −0.18 | Berthier et al., 2018 |
|  |  |  |  |
| Lemon Creek Glacier |
| Period (yyyy–yy) | Previous (m w.e. a−1) | This study (m w.e. a−1) | Source |
| 1957–89 | −0.35 | −0.23 | Marcus, 1995 |
| 1957–95 | −0.36 | −0.31 | Sapiano et al., 1998 |
| 1993–12 | −0.91 | −0.96 | Larsen et al., 2015 |
| 2000–16 | −0.78 | −1.11 | Berthier et al., 2018 |

**S–5 Annual Mass Balances**

**Table S3.** Annual mass balance time series (Ba) for Taku and Lemon Creek Glaciers. The source of geodetically calibrated Ba and ELA solutions is denoted as J Ba (JIRP time series) and R Ba (reanalyzed time series). NA represent years when the ELA migrated above the highest elevations of the glacier.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Year | Taku Ba (m w.e.) | Taku ELA (m) | Source | Lemon Creek Ba (m w.e.) | Lemon Creek ELA (m) | Source |
| 1946 | 0.13 | 980 | J Ba | - | - | - |
| 1947 | 0.53 | 900 | J Ba | - | - | - |
| 1948 | 0.68 | 870 | J Ba | - | - | - |
| 1949 | 1.09 | 800 | J Ba | - | - | - |
| 1950 | –0.01 | 1010 | J Ba | - | - | - |
| 1951 | –0.17 | 1160 | J Ba | - | - | - |
| 1952 | 0.33 | 950 | J Ba | - | - | - |
| 1953 | 0.02 | 1010 | J Ba | −0.40 | 1080 | J Ba |
| 1954 | 0.10 | 1160 | J Ba | −0.02 | 1025 | J Ba |
| 1955 | 1.14 | 950 | J Ba | 1.28 | 810 | J Ba |
| 1956 | 0.04 | 1010 | J Ba | −0.48 | 1075 | J Ba |
| 1957 | 0.13 | 980 | J Ba | 0.15 | 1000 | J Ba |
| 1958 | 0.38 | 780 | J Ba | −0.42 | 1040 | J Ba |
| 1959 | 0.52 | 1000 | J Ba | −0.74 | 1150 | J Ba |
| 1960 | 0.33 | 1010 | J Ba | −0.66 | 1130 | J Ba |
| 1961 | 0.65 | 930 | J Ba | −0.08 | 1080 | J Ba |
| 1962 | 0.56 | 915 | J Ba | −0.53 | 1110 | J Ba |
| 1963 | 0.74 | 950 | J Ba | 0.33 | 970 | J Ba |
| 1964 | 1.30 | 885 | J Ba | 1.20 | 885 | J Ba |
| 1965 | 0.96 | 900 | J Ba | 0.24 | 980 | J Ba |
| 1966 | 0.25 | 875 | J Ba | −0.33 | 1100 | J Ba |
| 1967 | 0.42 | 750 | J Ba | −0.44 | 1130 | J Ba |
| 1968 | 0.63 | 810 | J Ba | −0.06 | 1060 | J Ba |
| 1969 | 1.34 | 965 | J Ba | 0.37 | 1000 | J Ba |
| 1970 | 0.93 | 930 | J Ba | 0.07 | 1060 | J Ba |
| 1971 | 0.80 | 885 | J Ba | −0.24 | 1110 | J Ba |
| 1972 | 0.59 | 730 | J Ba | −0.49 | 1140 | J Ba |
| 1973 | 0.69 | 825 | J Ba | −0.36 | 1110 | J Ba |
| 1974 | 0.75 | 850 | J Ba | −0.21 | 1090 | J Ba |
| 1975 | 1.02 | 800 | J Ba | 0.44 | 1010 | J Ba |
| 1976 | 0.83 | 850 | J Ba | −0.09 | 1080 | J Ba |
| 1977 | 0.64 | 885 | J Ba | −0.32 | 1110 | J Ba |
| 1978 | 0.48 | 915 | J Ba | −0.64 | 1150 | J Ba |
| 1979 | 0.31 | 950 | J Ba | −0.48 | 1110 | J Ba |
| 1980 | 0.71 | 870 | J Ba | −0.11 | 1100 | J Ba |
| 1981 | 0.29 | 980 | J Ba | −0.65 | 1120 | J Ba |
| 1982 | 0.32 | 950 | J Ba | −0.27 | 1070 | J Ba |
| 1983 | −0.25 | 1085 | J Ba | −1.46 | 1220 | J Ba |
| 1984 | 0.81 | 875 | J Ba | −0.09 | 1010 | J Ba |
| 1985 | 1.57 | 600 | J Ba | 0.49 | 965 | J Ba |
| 1986 | 1.37 | 720 | J Ba | −0.35 | 1070 | J Ba |
| 1987 | 0.56 | 910 | J Ba | −0.68 | 1100 | J Ba |
| 1988 | 0.77 | 890 | J Ba | 0.27 | 1000 | J Ba |
| 1989 | −0.64 | 1115 | J Ba | −1.08 | 1130 | J Ba |
| 1990 | −0.28 | 1080 | J Ba | −0.96 | 1125 | J Ba |
| 1991 | 0.55 | 900 | J Ba | −0.22 | 1050 | J Ba |
| 1992 | 0.34 | 940 | J Ba | −0.50 | 1075 | J Ba |
| 1993 | 0.13 | 980 | J Ba | −0.82 | 1130 | J Ba |
| 1994 | 0.26 | 970 | J Ba | −0.60 | 1100 | J Ba |
| 1995 | −0.43 | 1219 | R Ba | −1.15 | 1150 | J Ba |
| 1996 | −0.21 | 1132 | R Ba | −1.42 | 1370 | J Ba |
| 1997 | −0.71 | 1279 | R Ba | −1.65 | 1400 | J Ba |
| 1998 | −0.23 | 1146 | R Ba | −0.89 | 1214 | R Ba |
| 1999 | 0.41 | 1056 | R Ba | −0.37 | 1113 | R Ba |
| 2000 | 0.88 | 948 | R Ba | −0.05 | 1105 | R Ba |
| 2001 | 0.37 | 964 | R Ba | −0.49 | 1115 | R Ba |
| 2002 | −0.21 | 1060 | R Ba | −0.88 | 1171 | R Ba |
| 2003 | −1.4 | 1391 | R Ba | −2.18 | NA | R Ba |
| 2004 | −0.77 | 1238 | R Ba | −1.78 | 1282 | R Ba |
| 2005 | −0.27 | 1078 | R Ba | −1.69 | 1406 | R Ba |
| 2006 | 0.23 | 1015 | R Ba | −0.8 | 1122 | R Ba |
| 2007 | 0.02 | 1015 | R Ba | −0.45 | 1096 | R Ba |
| 2008 | 0.58 | 1014 | R Ba | 0.39 | 1007 | R Ba |
| 2009 | −0.18 | 1015 | R Ba | −1.16 | 1241 | R Ba |
| 2010 | −0.21 | 1086 | R Ba | −1.26 | 1225 | R Ba |
| 2011 | −0.28 | 1085 | R Ba | −1.1 | 1179 | R Ba |
| 2012 | 1.13 | 984 | R Ba | 0.45 | 967 | R Ba |
| 2013 | −0.7 | 1149 | R Ba | −1.83 | NA | R Ba |
| 2014 | −0.61 | 1187 | R Ba | −1.8 | 1264 | R Ba |
| 2015 | −0.95 | 1216 | R Ba | −2.05 | 1226 | R Ba |
| 2016 | −0.88 | 1168 | R Ba | −2 | 1446 | R Ba |
| 2017 | −0.52 | 1175 | R Ba | −1.78 | NA | R Ba |
| 2018 | −1.36 | 1308 | R Ba | −2.74 | NA | R Ba |

**S–6 Comparison between JIRP and reanalyzed mass balances**

We explored several methodological differences between JIRP and reanalyzed time series, despite the strong correlation that was found between the two datasets: 1) the use of a fixed versus a time-variable hypsometry; 2) using a fixed versus a variable sloped mass balance profile in the ablation zone; 3) shifting the annual mass balance profile to intersect the ELA versus using a mass balance model to account for late-summer ablation.

 Our reanalyzed time series and those produced using a fixed 1948 hypsometry resulted a 0.07 m w.e. a-1 mean absolute difference to annual mass balance at both Taku and Lemon Creek Glaciers. This comparison suggests using a fixed hypsometry (Pelto and others, 2013) has little effect for the two glaciers, provided they are geodetically calibrated.

The average annual mass balance profiles used in the JIRP and reanalyzed time series are shown in **Table S4.** The shallower ablation zone slope in the reanalyzed time series may underestimated mass loss in the ablation zone, resulting in a larger geodetic calibration (**Table 6**). Similarly, the steeper accumulation zone slope in the JIRP time series may have overestimated accumulation on the upper glacier resulting in a larger geodetic calibration (**Table 6**) by.

**Table S4.** Mean annual mass balance profile slopes used in JIRP and reanalyzed time series for Taku and Lemon Creek Glacier

|  |  |  |
| --- | --- | --- |
|  | Taku Glacier | Lemon Creek Glacier |
| Zone | JIRP(m w.e. km−1) | Reanalyzed(m w.e. km−1) | JIRP(m w.e. km−1) | Reanalyzed(m w.e. km−1) |
| Ablation | 14.1 | 10.7 | 13 | 12.9 |
| Accumulation | 2.2 | 2.8 | 5 | 3.3 |

The effects of differences between balance profiles are compounded by variations in ELA estimates. JIRP ELAs are lower by 95 m on Taku Glacier and by 123 m on Lemon Creek Glacier. Using opportunistic satellite imagery (typically Landsat) to determine the ELA likely results in JIRP’s lower ELAs. This suggests an underestimation of ablation each year when compared to the output of our mass balance model.

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