

Multi-decadal elevation changes on Bagley Ice Valley and Malaspina Glacier, Alaska

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[1] Digital elevation models (DEMs) of Bagley Ice Valley and Malaspina Glacier produced by (i) Intermap Technologies, Inc. (ITI) from airborne interferometric synthetic aperture radar (InSAR) data acquired 4–13 September 2000, (ii) the German Aerospace Center (DRL) from spaceborne InSAR data acquired by the Shuttle Radar Topography Mission (SRTM) 11–22 February 2000, and (iii) the US Geological Survey (USGS) from aerial photographs acquired in 1972/73, were differenced to estimate glacier surface elevation changes from 1972 to 2000. Spatially non-uniform thickening, 10 ± 7 m on average, is observed on Bagley Ice Valley (accumulation area) while non-uniform thinning, 47 ± 5 m on average, is observed on the glaciers of the Malaspina complex (mostly ablation area). Even larger thinning is observed on the retreating tidewater Tyndall Glacier. These changes have resulted from increased temperature and precipitation associated with climate warming, and rapid tidewater retreat. **INDEX TERMS:** 1827 Hydrology: Glaciology (1863); 1640 Global Change: Remote sensing; 1863 Hydrology: Snow and ice (1827). **Citation:** Muskett, R. R., C. S. Lingle, W. V. Tangborn, and B. T. Rabus, Multi-decadal elevation changes on Bagley Ice Valley and Malaspina Glacier, Alaska, *Geophys. Res. Lett.*, 30(16), 1857, doi:10.1029/2003GL017707, 2003.

1. Introduction

[2] Fronting the Gulf of Alaska, the St. Elias and eastern Chugach Mountains contain the largest connected glacier and icefield complex in continental North America. The Bering and Malaspina Glacier systems (Figure 1) have a combined area of about 10,200 km²: 5200 km² and 5000 km² respectively [Molnia, 2001]. Most glaciers in this region are surge-type, with quasi-cycles of 5 to 30 years [Post, 1969]. Bagley Ice Valley (formerly Bagley Icefield), a 100 km long glacierized valley, is the main accumulation area of the Bering Glacier. Its last major surge occurred in 1993–95 [e.g., Lingle et al., 1993; Muller and Fleisher, 1995]. Crevassing on Bagley Ice Valley was observed in

August 1995 near the Canadian border [Herzfeld and Mayer, 1997]. Measurements of accelerated flow by InSAR indicated the surge propagated up-glacier almost to the ice divide [Fatland and Lingle, 2002]. Below the equilibrium line, heavy crevassing promoted increased ablation during subsequent summer seasons [Muskett et al., 2000]. The Malaspina Glacier (Figure 1), entirely in ablation area, is mostly fed by Seward Glacier, which is flanked on its upper north side by Mount Logan (5,959 m a.s.l.), in Yukon, Canada [Holdsworth and Sawyer, 1993].

[3] DEMs from the NASA SRTM in 2000, and from ITI in 2000, are used with USGS DEMs, whose data date from 1972/73, to derive multi-decadal spatial patterns of glacier elevation changes that have resulted from the combined effects of climate change and glacier dynamics.

2. Digital Elevation Models

[4] The SRTM, 11–22 February 2000, had the first spaceborne single-pass SAR interferometer [Eineder et al., 2001; Rosen et al., 2001]. Spearheaded by NASA and the National Imagery and Mapping Agency, SRTM was an international effort that included the Jet Propulsion Laboratory, DRL, and the Italian Space Agency. It yielded single-pass interferometric data, C and X-Bands, of land between 60°N and 54°S for processing into global DEMs. The InSAR antenna configuration (precise measurement of relative antenna location with laser rangefinders, star trackers and in-orbit Global Positioning System - GPS) resulted in elimination of mapping errors characteristic of repeat-pass satellite InSAR techniques [e.g., Joughin et al., 1996]. The subset of X-Band InSAR DEM we use has a nominal pixel size of 25-by-25 m, relative to the World Geodetic System 1984 (WGS-84) ellipsoid in the Universal Transverse Mercator (UTM) projection system. The nominal vertical accuracy is 6 m relative, 16 m absolute, and the nominal horizontal accuracy is 15 m relative, 20 m absolute, at the 90% confidence level.

[5] The ITI airborne survey 4–13 September 2000 covered Bagley Ice Valley in Alaska and Canada. Their InSAR system uses an X-Band dual antenna with onboard GPS and ground corner reflectors to minimize error sources

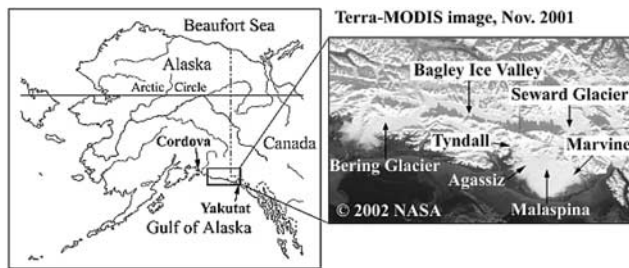


Figure 1. The Bering and Malaspina Glaciers in Alaska, USA, and Yukon, Canada. Bagley Ice Valley (formerly Bagley Icefield) was re-named by the US Board on Geographic Names.

[Intermap Technologies, 2000]. DEMs were derived with 10 m postings, WGS-84 ellipsoid UTM system, having root mean square accuracies of 2.5 m horizontal and 3 m vertical. Vertical accuracy of the ITI DEM on Bagley Ice Valley was verified using near-concurrent small-aircraft laser elevation profiling [see Echelmeyer *et al.*, 1996; Muskett *et al.*, 2001]. ITI provided versions of the Bagley Ice Valley DEMs with elevations relative to the Earth Gravity Model 1996 geoid and the WGS-84 ellipsoid.

[6] The USGS DEM data were derived from relief plate contours corresponding to 1:63,360 scale topographic maps dating from aerial photos in 1972/73 [USGS, 1990]. The data have 2 arc seconds latitude by 3 arc seconds longitude elevation postings relative to the North American Datum 1927. The vertical reference for elevation is the National Geodetic Vertical Datum 1929 (NGVD-29). Nominal vertical accuracy of the USGS DEMs is about 15 m (1/2 map contour interval).

3. Datum Transformations and Systematic Error Estimates

[7] USGS DEMs were mosaicked, re-projected onto the WGS-84 UTM horizontal datum (vertical datum not affected), and re-sampled to 30-by-30 m pixel size for co-registration. The SRTM DEM of Malaspina Glacier and the (mosaicked) ITI DEM of Bagley Ice Valley were also re-sampled to 30-by-30 m pixels. The SRTM and ITI DEM were adjusted to the GEOID99-Alaska datum (mean sea level datum) using data from the National Geodetic Survey [National Oceanographic Atmospheric Administration, USA]. We take the GEOID99-Alaska datum to be the best approximation of sea level for Alaska, equivalent to NGVD-29.

[8] The USGS DEMs are the dominant source of elevation errors. Systematic height errors likely have two sources: (1) inadequate photogrammetric vertical control, and (2) poor stereographic resolution in flat terrain, causing contour mislocation and shape exaggeration, i.e. “contour floating.”

[9] Vertical control errors of the USGS DEMs were estimated relative to the modern DEMs in low-slope (0 to 2°) areas on Juniper Island (a Bagley Ice Valley nunatak at 60°37'N, 142°21'W, ~1300 m a.s.l.), and a sparsely vegetated area off the Malaspina Glacier margin near Cape Sitkagi (59°44'N, 140°45'W, ~10 m a.s.l.). Juniper Island was found to be 9 ± 27 m (200 points) too low and the

area near Cape Sitkagi was found to be within 0 ± 10 m (200 points) respectively.

[10] Height errors caused by “contour floating” were estimated by comparing USGS DEM contour shapes to corresponding ITI and SRTM DEM contour shapes on Bagley Ice Valley and Malaspina Glacier, respectively. We assume corresponding contours should have the *same shapes* (not absolute elevations) in 1972/73 and 2000. This assumption was tested on Tyndall Glacier, where massive thinning has occurred (Table 1). The USGS contours showed little exaggeration (0 ± 2 m) although some up-glacier shift was evident due to thinning. Bagley Ice Valley (accumulation area) had a mean up-glacier exaggeration of the USGS contours relative to the ITI contours suggesting the 1972/73 surface was mapped about 4 ± 3 m too low. Malaspina Glacier (ablation area) had a mean down-glacier exaggeration of the USGS contours relative to the SRTM contours suggesting the 1972/73 surface was mapped about 6 ± 3 m too high.

[11] Lastly, a correction for cumulative snow depth (Figure 2, upper curve) on Malaspina Glacier was applied to adjust the SRTM DEM to a late summer surface for comparison to the USGS DEM using the Precipitation-Temperature-Area-Altitude model of Tangborn [1999] (Figure 2 lower curve), with summer snow density measurements from Sharp [1951, 1958] and Alford [1967], and a winter density adjustment estimate based on Zwally and Li [2002].

4. Results

[12] Elevation changes from 1972/73 to 2000 on Bagley Ice Valley, Malaspina Glacier and their tributaries were estimated by subtracting the USGS DEMs (1972/73) from the ITI (September 2000) and SRTM (February 2000) DEMs (Figure 3). The results (Table 1) are corrected for systematic errors in the USGS DEMs, and winter snow depth in the case of the SRTM DEM. Estimates indicate spatially non-uniform thickening and thinning of Bagley Ice Valley and portions of its tributary glaciers (e.g., Quintino Sella) (Figure 3a, Table 1). Above the equilibrium line, Bagley Ice Valley thickened by 10 ± 7 m, on average. Thinning and local thickening of Malaspina Glacier are also spatially non-uniform (Figure 3b, Table 1). The total surface area of the Malaspina Glacier complex (Agassiz, Seward Lobe, Marvine and Hayden Glaciers) lowered by 47 ± 5 m, on average. Tyndall Glacier, a rapidly retreating tidewater glacier at Icy Bay (Figure 1), thinned by 63 ± 5 m, on average. The terminus of Tyndall Glacier retreated about

Table 1. Summary of Elevation Changes From 1972/73 to 2000

Glacier (m)	Average	Thinning ^a (m)	Thickening ^a (m)	Rate (a) (m a ⁻¹)
Bagley I. (b)	-30 ± 9	-50 ± 9		-1.1 ± 0.3
Bagley I. (c)	10 ± 7	-40 ± 7	100 ± 7	0.4 ± 0.2
Quintino S.	-100 ± 11	-230 ± 11		-3.6 ± 0.4
Agassiz	-29 ± 4	-100 ± 4	50 ± 4	-1.1 ± 0.1
Seward L.	-49 ± 5	-120 ± 5	20 ± 5	-1.8 ± 0.2
Marvine	-58 ± 3	-160 ± 3	10 ± 3	-2.1 ± 0.1
Hayden	-39 ± 3	-100 ± 3	50 ± 3	-1.4 ± 0.1
Tyndall	-63 ± 5	-400 ± 5	20 ± 5	-2.3 ± 0.2

^a(local maxima; a - minus indicates thinning; b - from equilibrium line altitude, ~1360 m, down to ~1130 m a.s.l.; c - above equilibrium line).

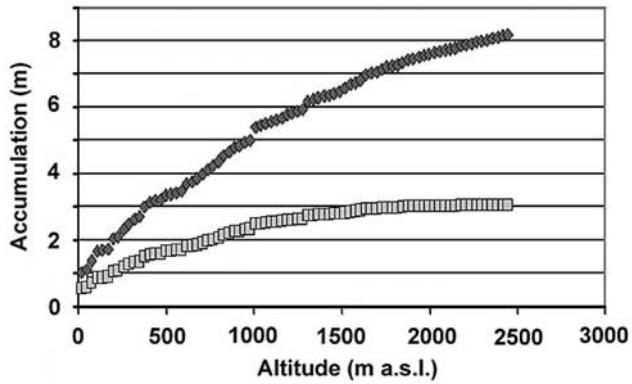


Figure 2. Simulated accumulation, water equivalent (lower curve) and corresponding estimated snow depth profile (upper curve) on Malaspina and Seward Glaciers, September 1999 through February 2000, based on measured summer densities from *Sharp* [1951, 1958], and *Alford* [1967] and a winter density estimate based on *Zwally and Li* [2002].

13 km up-fjord during the 28 year period, mostly before 1990 [*A. Post*, per. comm.].

5. Summary and Interpretation

[13] Substantial thinning was observed during the 28-year period from 1972/73 to 2000 in the ablation areas of the Malaspina Glacier system, including Seward Lobe and Agassiz, Marvine, and Hayden glaciers. Greater thinning was observed on Tyndall Glacier, a tidewater glacier which discharges into Icy Bay (Figure 1). In contrast, significant thickening was observed on Bagley Ice Valley, Bering Glacier's accumulation area, during the same 28-year period. These results were determined by differencing the USGS DEMs, derived from aerial photography acquired in 1972/73, with DEMs derived from InSAR data acquired in September 2000 by ITI, and February 2000 by the SRTM. Our results are consistent with those of *Arendt et al.* [2002], who found substantial thinning of 67 glaciers throughout Alaska, Yukon, and NW British Columbia in their ablation areas, and lesser thinning, or even slight thickening, at higher elevations in their accumulation areas, from the mid-1950s to 2001.

[14] National Weather Service (NWS) data (1973) shows regional mean annual precipitation of 2 to 6 m [*Mayo*, 1989]. A high-altitude core (69.6°N, 140.6°W, 5340 m a.s.l.) on Mt. Logan shows accumulation increasing since about 1850, with the most rapid increase since 1976 [*Moore et al.*, 2002]. At sea level, NWS data averaged for Yakutat and Cordova (Figure 1) show daily mean temperature and precipitation increased during 1976–2000 relative to 1950–1975 (Figure 4). In particular, both temperature and precipitation were substantially higher in winter, with precipitation also substantially higher in fall (Figure 4). The measured increased precipitation at both high and low elevations suggest this was a contributing factor to the increased elevations observed on Bagley Ice Valley (Figure 3a), in addition to surge dynamics [*Fatland and Lingle*, 2002]. Decadal variation in the snow accumulation rate and temperature will also have affected the firn densification rate, thus affecting changes in surface elevation [*Zwally and Li*,

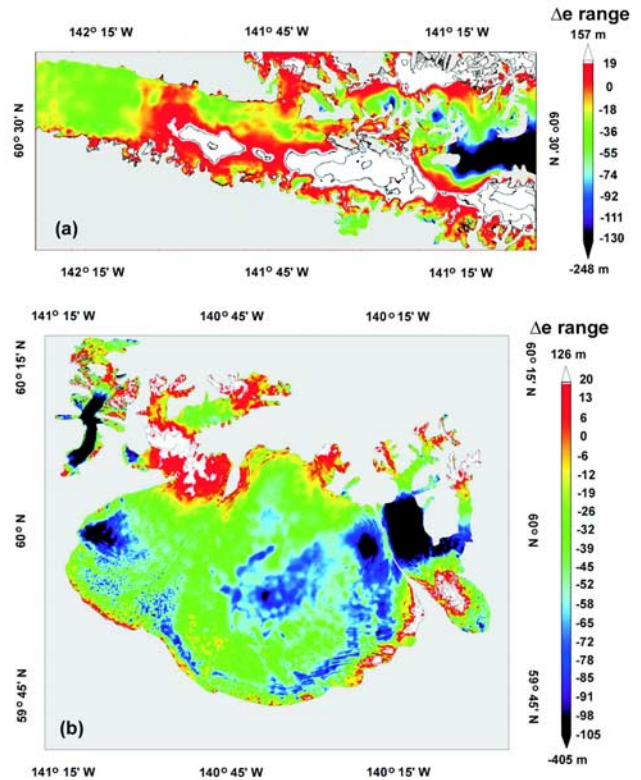


Figure 3. Surface elevation changes on: (a) Bagley Ice Valley complex including portions of Jefferies (top center) and lower Quintino Sella Glacier (center right); and (b) Malaspina Glacier complex including Agassiz (left), Seward lobe (center), Marvine (right), and Hayden Glacier (far right). The tidewater Tyndall Glacier is at upper left. Thirty meter contours are shown in high range (white) for clarity.

2002]. The USGS and the ITI DEM were each acquired 5 years after the 1965–67 and 1993–95 surges, respectively; however, a very large surge also occurred in 1957–60 [e.g., *Lingle et al.*, 1993]. We speculate that the surface of Bagley

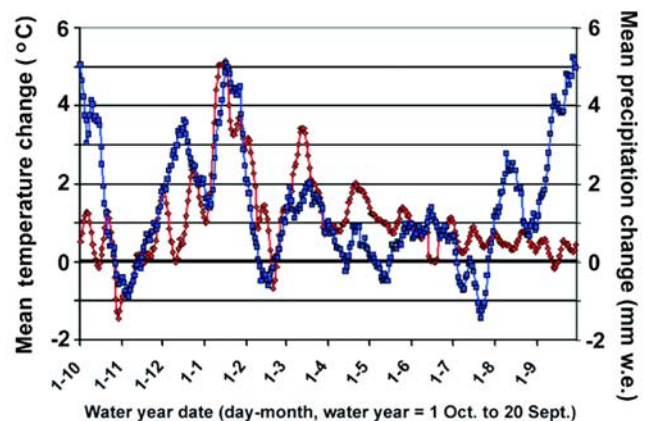


Figure 4. Twenty-five year mean temperature (red) and precipitation (blue) changes, 1976–2000 minus 1950–1975, average of Yakutat and Cordova NWS data (at sea level), plotted on a daily basis. Both temperature and precipitation were substantially increased during the more recent period on most days, particularly during winter and also, in the case of precipitation, during fall.

Ice Valley may have been drawn down so far by the two closely-spaced surges of 1957 and 1965 that it is still recovering (gaining elevation), despite the presumably more modest drawdown of the 1993–95 surge.

[15] At low altitude, the large elevation decreases observed on the Malaspina ablation areas (Figure 3b) are well correlated with increased temperatures at Yakutat and Cordova during 1976–2000, relative to 1950–1975 (Figure 4). Increased summer and fall precipitation (rain, Figure 4) probably also has contributed to increased melting. The Malaspina Seward lobe surges periodically, most recently in 1987–88, as does Marvine Glacier [*A. Post*, per. comm.]. Agassiz Glacier has a pulse-like flow, but surface lowering caused by increased ablation appears to be the dominant effect.

[16] The dramatic retreat and thinning observed on Tyndall Glacier is mostly due to rapid tidewater retreat, caused by tidewater instability [*Meier and Post*, 1987; *O'Neil et al.*, 2001]. This was interrupted by a major surge in 1964, followed by continued retreat and thinning [*A. Post*, per. comm.].

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