Ice elevations and surface change on the Malaspina Glacier, Alaska

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[1] Here we use Ice, Cloud and land Elevation Satellite (ICESat)-derived elevations and surface characteristics to investigate the Malaspina Glacier of southern Alaska. Although there is significant elevation variability between ICESat tracks on this glacier, we were able to discern general patterns in surface elevation change by using a regional digital elevation model (DEM) as a reference surface. Specifically, we report elevation differences between ICESat Laser 1–3 observations (February 2003 – November 2004) and a Shuttle Radar Topography Mission (SRTM)-derived DEM from February 2000. Elevation decreases of up to 20–25 m over a 3–4 year time period were observed across the folded loop moraine on the southern portion of the Malaspina Glacier.
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1. Introduction

[2] While the primary goal of the Ice, Cloud and land Elevation Satellite (ICESat) is to measure elevation changes of the vast polar ice sheets (B. Schutz et al., ICESat mission overview, submitted to *Geophysical Research Letters*, 2005, hereinafter referred to as Schutz et al., submitted manuscript, 2005), it also collects data over large temperate mountain glaciers (e.g. Alaska, Patagonia), which are sensitive indicators of climate change. These mountain glaciers, however, generally have rougher surfaces and steeper regional slopes than the ice sheets for which ICESat was optimized. Rather than averaging over large regions or relying on crossovers, we worked with individual ICESat footprint returns to estimate glacier elevations and surface characteristics. In the northern hemisphere at latitudes <59°N, in the southern hemisphere outside of Antarctica, and globally during Laser 1 operations, ICESat tracks do not generally repeat within 100 m unless the ground track is specifically targeted. As we show in this paper, a regional SRTM-derived DEM can be used along with ICESat to detect general patterns in elevation change for surfaces with variable slope and roughness.

[3] The glaciers of the southeastern Alaska coastal region include some of largest temperate glaciers on Earth and may contribute one third of the total glacier meltwater entering the global ocean [*Arendt et al.*, 2002; *Molnia*, 2005]. During the time period 1988–1998 southeastern Alaskan glaciers showed a tendency toward earlier glacier melt onset and longer ablation seasons [*Ramage and Isacks*, 2003], resulting in increased glacier wastage. The Malaspina Glacier (and tributaries), has an area of ~5,000 km^2, with the largest piedmont lobe of any temperate glacier. The entire lobe, which lies at elevations below 600 m, is within the ablation zone (Figure 1).

[4] In this study, we report ICESat-derived elevations and waveform extent along a center line profile of the Malaspina piedmont lobe. In addition to characterizing surface features along this portion of the glacier, we examined the three Laser 1 near-repeat observations to demonstrate the utility of ICESat for glacier elevation and change studies outside the exact repeat mode of the polar region. Also, we report elevation differences across portions of the glacier between ICESat Laser 1–3 observations (Feb. 2003–Nov. 2004) and a SRTM-derived DEM from observations in Feb. 2000. We use the elevation change results across the Malaspina piedmont lobe, along with earlier studies, to address the spatial and temporal variability in surface elevation due to ongoing glacier wastage and a recent surge.

2. Data Characteristics

2.1. ICESat

[5] We examined all available ICESat data over the Malaspina Glacier from Laser 1–Laser 3a, filtered for clouds using the 1064 and 532nm ICESat atmospheric backscatter plots (Figure 1). The tracks which we analyzed in more detail are given in Table 1. We requested off-nadir pointing (Schutz et al., submitted manuscript, 2005) of T163 (91-day) to T29 (8-day) starting with Laser 2b [163* in Figure 1]. ICESat received waveforms record 1064 nm wavelength laser energy as a function of time reflected from footprints spaced 172 m apart along profiles. Over most of the Malaspina piedmont lobe the waveforms from individual ICESat footprints have a simple peak. Therefore, we used the GLA06 elevations [*Brenner et al.*, 2003]. For comparison to the SRTM data the ICESat location and elevations were transformed from the TOPEX ellipsoid to WGS84 EGM-96 reference system using the approach given by C. Carabajal and D. Harding (ICESat validation of Shuttle Radar Topography Mission C-band digital elevation models, submitted to *Geophysical Research Letters*, 2005, hereinafter referred to as Carabajal and Harding, submitted manuscript, 2005). Based on a calibration of the ICESat releases, the errors range from ~0.15–1.20 m in elevation and ~18–24 m in horizontal position [*Luthcke et al.*, 2005] for the data given in Table 1.

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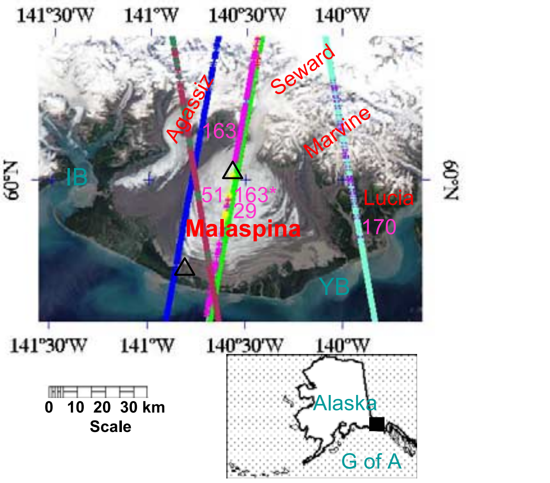

Figure 1. Moderate Resolution Imaging Spectroradiometer (MODIS) image from NASA's Aqua satellite of the Malaspina Glacier acquired August 9, 2003, with ICESat tracks overlaid (track numbers are given to the right in pink, T163* are T163 with off-nadir pointing to T29). The location of the first and seventh ice thickness estimates (Table 2) are shown by triangles. Glacier names are given in red. IB = Icy Bay, YB = Yakutat Bay. Below the MODIS image is an outline of Alaska with a black box indicating the location of the study region. G of A = Gulf of Alaska.

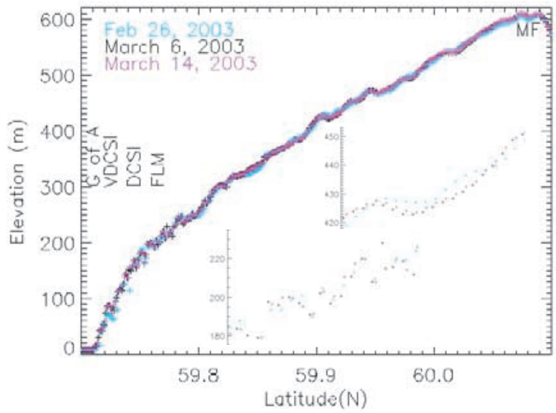

Figure 2. Plot of three near repeat elevation profiles as a function of latitude across the center of the Malaspina piedmont lobe from ICESat Laser 1 (T29 in Figure 1). Inserts: (a) Elevation profile enlarged between 59.75–59.78°N. (b) Elevation profile enlarged between 59.90°–59.93°N. Elevation variability is most apparent between the Feb. 26 profile located ~400 m to the west of the March 6 and 14 profiles. Different regions of the piedmont lobe (from south to north): VDCSI = vegetated debris covered stagnant ice, DCSI = debris covered stagnant ice, FLM = folded loop moraines, MF = Malaspina fault. We used the one cloud-free track (March 6, 2003) to look for systematic variations in waveform extent. Along the lower Malaspina, waveform extent systematically decreased from the terminus region to the northern extent of FLM. The upper Malaspina portion (north of 59.84°N) is characterized by moderate wavelength (2–3 km) undulations. The increased ice thickness on the northern portion of the piedmont (Table 2) accounts for the smoother surface features.

2.2. SRTM

[6] Southern Alaska is located at the northern extent of the SRTM orbit (see http://www.jpl.nasa.gov/srtm and *Farr and Kobrick* [2001]). SRTM observations were made of the entire Malaspina piedmont lobe but there is some missing data, especially above 60.05°N on steep north facing slopes. The C-band swaths were processed into a DEM by the Jet Propulsion Laboratory. We used the unfinished, research 1 arc sec data version of SRTM which gives orthometric elevation in meters above the EGM96 geoid in the WGS84 reference system. The mean ICESat minus SRTM difference for continental North America with <20% tree cover and <5 m of roughness is −0.60 ± 3.46 m (Carabajal and Harding, submitted manuscript, 2005). *Rignot et al.* [2001] compared C-band TopSAR and laser altimetry measurements over Alaska glaciers and found little C-band signal penetration over exposed ice; however, over snow covered areas signal penetration of several meters occurred.

3. ICESat Elevation and Surface Characteristics Along a Center Profile

[7] The elevations from the Laser 1 Track 29 (T29) profiles across the center lobe of the Malaspina piedmont are shown in Figure 2 and additional track information is given in Table 1. The USGS estimated the ice thickness along a southwest to northeast profile (Table 2).

[8] The waveform extent of the returned ICESat signal varied systematically from narrower waveforms on the smoother, lower gradient upper Malaspina region to wider and at times multi-peaked wavefirns on the rougher, higher slope regions near the terminus. Early March is prior to the spring melt season so some topographic features were masked by the uneven distribution of snow. The waveform extent can be used to calculate the within-footprint slope assuming no roughness contributes to waveform widening or the roughness assuming no slope contribution [*Brenner et al.*, 2003]. Since we are currently in the process of validating the ICESat within footprint slope and roughness estimates, we report variations in waveform extent.

Table 1. ICESat Tracks Used in Differenced Profiles

Date	Laser: Track #, Cycle	Data Release
Feb. 26, 2003	Laser1: 29, 2	18
March 6, 2003	Laser1: 29, 3	18
March 14, 2003	Laser1: 29, 4	18
November 1, 2003	Laser2a: 163, 2	21
Feb. 26, 2004	Laser2b: 51, 2	16
October 20, 2004	Laser3a: 170, 2	22

Table 2. Ice Elevation and Thickness Across the Malaspina Piedmont Lobe [*Molnia and Jones*, 1989; B. Molnia et al., personal communication, 2005]

Elevation (asl), m	Ice Thickness, m
170	363
180	500
360	615
475	786
485	723
534	786
579	864

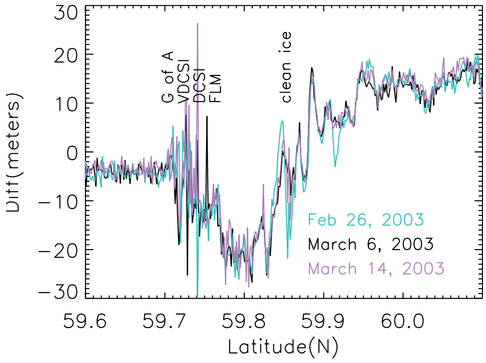

Figure 3. Plot of Laser 1 ICESat minus SRTM elevations along three center line profiles (T29 in Figure 1) as a function of latitude. Along the portion of the profile over the Gulf of Alaska (59.6°N to 59.68°N) there is a systematic bias between ICESat and SRTM that ranges from 2–6 m. Significant elevation decrease between the winter of 2000 and 2003 is shown from the terminus region to ~59.85°N. In contrast, the northern-most portion of the Malaspina Glacier increased in elevation; this region is hypothesized to be the ice receiving area for a surge on the lower Seward Glacier. Abbreviations are as given in Figure 2.

[9] For the southern-most portion of the Malaspina (59.72°–59.82°) the waveform extent decreases systematically as a function of distance from the terminus (Figure 2). Since the terminus region is partially vegetated in the south, we also examined the elevation of the waveform signal start (highest point, probably the top of vegetation [*Harding and Carabajal*, 2005]) and waveform signal end (lowest ground return). On the center line profile the difference between the waveform signal start and signal end was up to 20 m in the region of vegetated, debris-covered ice (VDCSI, Figure 2). This region contains a number of steep-walled circular thermokarst depressions with >10 m of relief as well.

[10] For the northern portion of the Malaspina piedmont lobe (59.84°–60.1°) there are variations in waveform extent associated with surface undulations (Figure 2). Specifically, the laser pulse width broadened (greater within footprint roughness and/or slope) on the surface highs relative to the lows on this segment of the profile. Based on field work and aerial photography (B. Molnia, 1986, 2002–5) the topographic highs are more crevassed than the lows.

4. ICESat and SRTM Differenced Elevations

[11] The ICESat elevation profiles with low cloud cover (Table 1) over the Malaspina piedmont lobe were differenced from SRTM derived elevations using the approach given by Carabajal and Harding (submitted manuscript, 2005). Here we report the elevation differences without stating the water equivalent. We estimated the systematic vertical error between the ICESat profiles and SRTM values by computing the apparent elevation differences over the ocean and areas of fixed topography for all tracks in Table 1. Over the ocean the SRTM DEM values were systematically higher than ICESat elevations by 2–6 m (Figure 3). *Muskett et al.* [2003b] found that the X-band SRTM was systemically higher than aircraft SAR altimetry data by 2.7 ± 0.8 m across the outwash plain of the Malaspina Glacier.

[12] Surface elevation changes on the glacier have a seasonal and annual component due to differential snow accumulation, firn compaction, and ice melting. Although we were able to estimate a seasonal elevation change on a tributary of the Seward Glacier and on the Upper Seward Glacier from 163*, cloud cover over the Malaspina piedmont lobe during most of these data takes was significant. Based on ICESat-ICESat elevation change from exact repeat tracks on the upper Bering Glacier (at an altitude of ~600 m), we estimated 2–3 m of elevation increase between early November 2003 and early March 2004. *Muskett et al.* [2003a] estimated the amount of snow accumulation from September 1999 through February 2000 as a function of elevation from the precipitation and temperature data from two nearby coastal National Weather Service (NWS) stations (http://climate.gi.alaska.edu). Using a Precipitation-Temperature-Area-Altitude model, they calculated the simulated snow accumulation to be ~1 m at sea-level and almost 4 m at an altitude of 600 m. Comparison of the ICESat observations on the Bering Glacier in the winter of 2003/2004 (2–3 m) to Muskett's predicted snow accumulation at 600 m (4 m) suggests that snow accumulation over the winter of 2003/2004 was probably lower than the winter 1999/2000. This result is supported by a comparison of monthly precipitation from Jan.–April at the NWS site Yakutat. We assume the same general situation for the Malaspina piedmont lobe. Although SRTM elevations from February 2000 could be slightly higher due to more snow accumulation that year, some C-band signal penetration through snow is likely as well.

[13] We used the three Laser 1 repeat track observations with slightly different ICESat and SRTM locations to assess the repeatability of the elevation differences. All three differenced profiles have similar long-wavelength features (>5 km) and the closer tracks, March 6 and March 14, have similar short wavelength (<1 km) features as well (Figure 3).

[14] The ICESat minus SRTM differenced elevations (with smoothing) for T29 (cycle 3), T51, and T163 (Table 1) are given in Figure 4. All three profiles show thinning in the lower reaches of the Malaspina Glacier; >5 m of thinning was observed over a ~10 km region on the centerline profile and ~30 km on the western piedmont lobe. This maximum surface elevation decrease occurred over the folded loop moraines (Figures 1 and 4). North of 59.9°, the center line profile indicates an elevation increase. The other profiles show only modest increases locally. The observed elevation increase of the upper piedmont lobe on the center line profile is likely due to a 1999–2002 surge of the lower Seward Glacier into the center and west side of the primary Malaspina lobe [*Muskett et al.*, 2003b] as coastal snowfall at Yakutat, Alaska for winter 2003 was the lowest on record (http://climate.gi.alaska.edu/Climate/Location/TimeSeries/Data/yakSn). A portion of Laser 3a T170 (59.8°–60.00°N) showed elevation decrease (5–20 m) between Feb. 2000 and Oct. 2004. This may be partially due to seasonal differences in snow accumulation, but thinning of the Lucia Glacier is suggested as well.

4.1. Comparison to Earlier Elevation Change Results

[15] Thinning of the piedmont lobe has been estimated to be 85 to 129 m in the last 100 years (0.8–1.3 m/yr average, summary given by *Molnia* [2005]). Periodic surges of

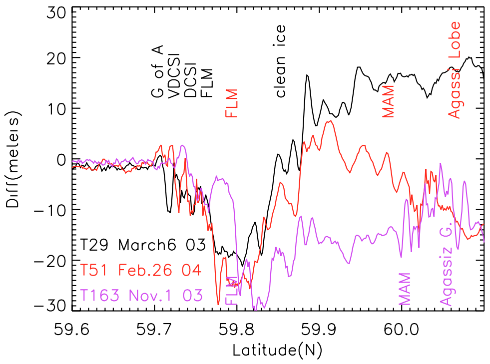

Figure 4. Plot of ICESat minus SRTM derived elevations along T29(3), T51 and T163 as a function of latitude with a boxcar averaging for a width of 5 values. These differences have an estimate of the vertical bias (−2.5 m) removed. All three profiles show elevation decrease in the region of the folded loop moraine. Note that the only profile with ice elevation increase spanning a region >10 km was T29 from the winter 2003. MAM = Malaspina-Agassiz lobe moraine, other abbreviations are as given in Figure 2.

different Malaspina tributaries affect portions of the Malaspina piedmont lobe that would lead to spatially and temporally varying estimates of surface elevation change. [*Muskett et al.*, 2003a] compared a 1972/73 USGS DEM to SRTM across the Malaspina that indicated mean ice thinning of 47 m ± 5 m (−1.8 m/yr) with localized thinning of up to 160 m (−6.4 m/yr). This time period, however, included a surge of the eastern Seward lobe and the Marvine Glacier. A surge of the western Seward lobe (1999/2002) caused yet another pattern of elevation changes.

5. Summary and Future Work

[16] We have shown that ICESat measurements can be used to estimate important characteristics of a temperate glacier, although there may be significant elevation variability between near-repeat ICESat tracks. Additionally, we were able to discern general patterns in surface elevation change by using a regional SRTM DEM as a reference surface. Cloud coverage reduced the potential seasonal and annual change signatures from the ICESat data. We anticipate further applications of ICESat to ICESat comparisons as the errors are reduced and additional data are acquired.

[17] **Acknowledgments.** We thank the ICESat science project and the NSIDC for distribution of the ICESat data (see http://icesat.gsfc.nasa.gov and http://nsidc.org/data/icesat/) and the science, instrument, software, and spacecraft teams for their extraordinary effort to achieve the data quality shown in this study. J. Sauber especially thanks science team member J. Bufton for asking her to join his GSFC ICESat group 7 years ago and B. Schutz for setting up the off-nadir acquisitions over the Malaspina and Bering Glaciers. R. Muskett thanks Craig Lingle for support. We appreciated the constructive comments and suggestions from Helen Fricker Joan Ramage and an anonymous reviewer. We thank J. Zwally and the ICESat project office and W. Abdalati of NASA Cryospheric Sciences Program for supporting this work under NASA grant 921-621-65-01.

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