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Elevation Change of Drangajökull, Iceland from Cloud-Cleared ICESat Repeat Profiles and GPS Ground-Survey Data

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ABSTRACT

Located on the Vestfirðir (Northwest Fjords), Drangajökull is the northernmost ice cap in Iceland. Currently, the ice cap exceeds 900 m in elevation and covered an area of ~146 km^2 in August 2004. It was about 204 km^2 in area during 1913-1914 and so has lost mass during the 20th century. Drangajökull's size and accessibility for GPS surveys as well as the availability of repeat satellite altimetry profiles since late 2003 make it a good subject for change-detection analysis. The ice cap was surveyed by four GPS-equipped snowmobiles on 19-20 April 2005 and has been profiled in two places by Ice, Cloud, and land Elevation Satellite (ICESat) 'repeat tracks,' fifteen times from late 2003 to early 2009. In addition, traditional mass-balance measurements have been taken seasonally at a number of locations across the ice cap and they show positive net mass balances in 2004/2005 through 2006/2007. Mean elevation differences between the temporally-closest ICESat profiles and the GPS-derived digital-elevation model (DEM) (ICESat - DEM) are about 1.1 m but have standard deviations of 3 to 4 m. Differencing all ICESat repeats from the DEM shows that the overall elevation difference trend since 2003 is negative with losses of as much as 1.5 m a^{-1} from same season to same season (and similar elevation) data subsets. However, the mass balance assessments by traditional stake re-measurement methods suggest that the elevation changes where ICESat tracks 0046 and 0307 cross Drangajökull are not representative of the whole ice cap. Specifically, the area has experienced positive mass balance years during the time frame when ICESat data indicates substantial losses. This analysis suggests that ICESat-derived elevations may be used for multi-year change detection relative to other data but suggests that large uncertainties remain. These uncertainties may be due to geolocation uncertainty on steep slopes and continuing cloud cover that limits temporal and spatial coverage across the area.

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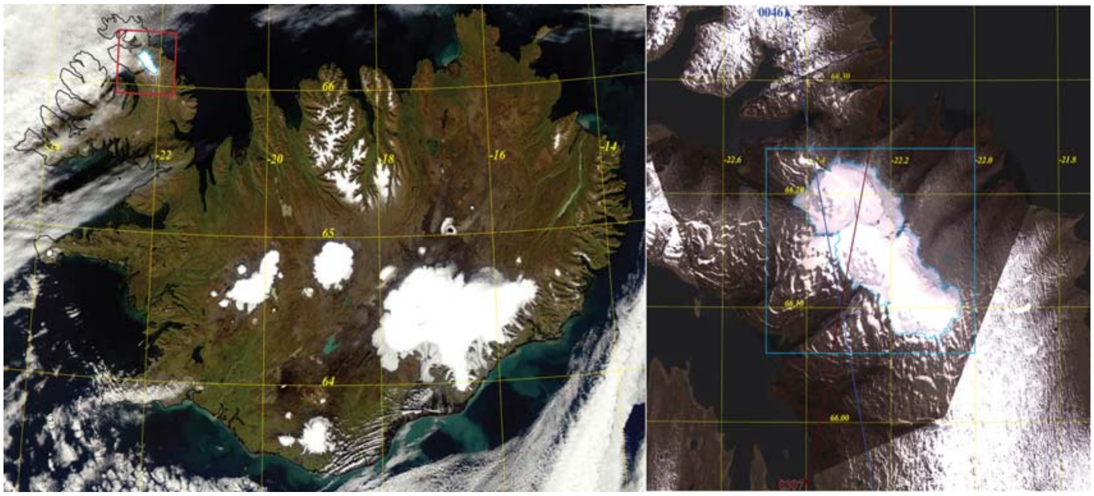

Figure 1a, b. An annotated Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) image of Iceland on 9 September 2002 (1a, left). The red box in NW Iceland over Drangajökull is shown in more detail at right (1b) using two Landsat Enhanced Thematic Mapper+ (ETM+) images (the 23 May 2003 ETM+ image had substantial snow cover whereas the 1 September 2000 ETM+ image better shows the ice cap margins but had more cloud cover and so was cropped and merged with the 2003 image). Note the locations of the two ICESat reference tracks across the ice cap. Track 0046 is ascending (blue) across the NW corner of Drangajökull and Track 0307 is descending (red) across the ice cap's highest ice dome. Note the cloud cover in the MODIS image and the proximity of the study site to fjords and open ocean water.

INTRODUCTION

Located in Vestfirðir (Northwest Fjords), the ~146 km^2 Drangajökull is the northernmost glacier in Iceland and it is currently ~20 km long by ~7 km wide (Figure 1a and b, Sigurðsson, 2005)). Along its crestal divide, four distinctive and one minor ice domes rise above 800 m, with the highest dome rising to 918 m (as of August 2004). The area and elevation of the ice cap have decreased during the 20th Century when compared with 1913-1914 Danish Geodetic Survey plane table maps (204 km^2 Thorarinsson, 1943; 1958), with sequential ground photographs of Holleifsborg Mountain (Figure 2, feature c), and measurements on Landsat Multispectral Scanner (MSS) images (160 km^2) acquired during the 1970s (Björnsson, 1980; Williams, 1983). Drangajökull's compactness and relative accessibility make it suitable for repeated field observations and measurements as well as analysis and validation of data acquired by airborne and/or satellite sensors. Ice caps, and their associated outlet glaciers in the North Atlantic region, such as those in Iceland, are sensitive to climate variability because of their size and geometry (Orelemans, 2001). Small changes in summer temperature can cause significant changes in the areal extent of an ice cap's ablation and accumulation areas and, if such changes persist from year to year, in its mass balance. Recent warming trends that have been observed in the North Atlantic (Arctic Climate Impact Assessment, 2005; Hanna et al. 2004) may be reflected in thinning and recession of outlet glaciers and other ice-sheet (e.g., Hall et al., 2008) and ice cap margins. Because the latitude, proximity to the North Atlantic Ocean, and topography of Drangajökull are similar to some areas in the southeastern coastal region of Greenland, this study of elevation changes over time serves as a test case for similar area ice-mass studies along and adjacent to the margin of the Greenland ice sheet. In summary, this effort assesses the capability of Ice, Cloud, and land Elevation Satellite (ICESat) laser altimetry profiles (Figure 2 and Table 1) to measure changes from 2003–2009 relative to a topographic data set acquired by Global Positioning System

(GPS) ground surveys over the ice cap by Iceland National Energy Authority (INEA), U.S. Geological Survey, and other personnel on 19-20 April 2005.

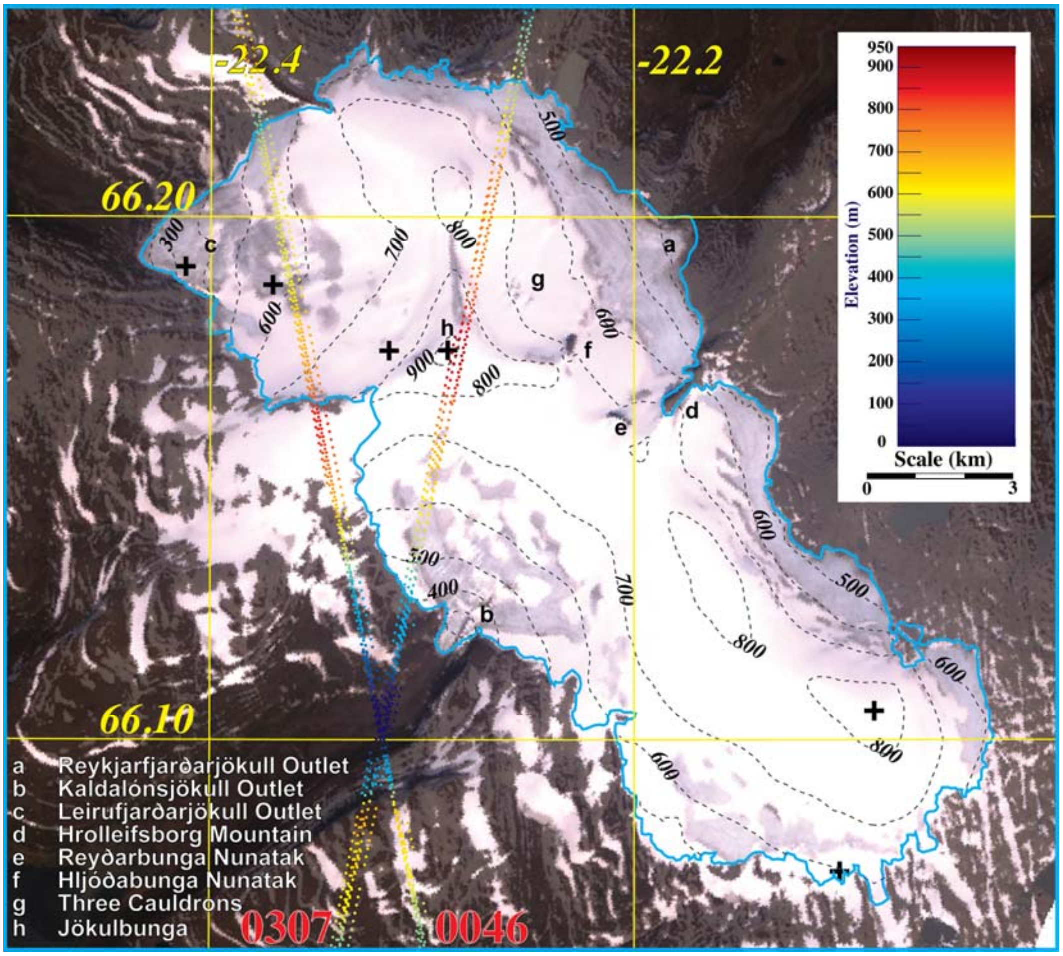

Figure 2. Drangajökull and its environs from a 1 September 2000 Landsat ETM+ image. This base map shows the locations of the laser footprints from each repeat of the two ICESat profiles that passed the initial cloud filtering colored by elevation (see color scale). The laser-altimetry data do not exactly repeat and have a ground spacing of ~170 m along track when skies are clear (some passes are incomplete due to clouds, see Figure 3). The Drangajökull DEM contour lines derived from GPS ground profiles on 19-20 April 2005 are shown by dashed lines. Some specific landmarks in the area (see key at lower left) are also shown as the locations of the stakes (+) used in the annual mass-balance measurements. Note that Track 0046 crosses a major west-facing, surge-type, outlet glacier, Leirufjarðarjökull (c) and that 0307 crosses the highest dome, Jökulbunga (h, 918 m), and so samples both south-facing and northeast facing slopes.

ICESat Data	ICESat Track	Data Release	Profile Date	Shots On DEM	Trans. Energy (μJ, avg.)	Rec. Energy (aJ, avg.)	N.H. Season
2A	0046	428	10/24/03	32	74175	4905	Fall
2A	0307	428	11/11/03	0	64411	4020	Fall
2B	0046	428	2/25/04	32	49014	19825	Winter
2B	0307	428	3/14/04	62	40308	2485	Winter
2C	0046	428	5/26/04	33	16052	2139	Spring
2C	0307	428	6/13/04	0	8000	N/A	Spring
3A	0046	428	10/12/04	0	60800	N/A	Fall
3A	0307	428	10/29/04	37	67669	19478	Fall
3B	0046	428	2/27/05	28	61931	22777	Winter
3B	0307	428	3/16/05	0	54900	N/A	Winter
3C	0046	428	5/29/05	31	48373	7609	Spring
3C	0307	428	6/15/05	32	44465	12175	Spring
3D	0046	428	10/29/05	0	43368	4696	Fall
3D	0307	428	11/16/05	64	37152	15924	Fall
3E	0046	428	3/2/06	0	37031	6363	Winter
3E	0307	428	3/20/06	18	32200	7413	Winter
3F	0046	428	6/1/06	0	32600	N/A	Spring
3F	0307	428	6/19/06	21	32460	5421	Spring
3G	0046	428	11/2/06	0	28500	N/A	Fall
3G	0307	428	11/19/06	2	24762	12487	Fall
3H	0046	428	3/20/07	0	23100	N/A	Spring*
3H	0307	428	4/6/07	2	21957	477	Spring*
3I	0046	428	10/10/07	0	20800	N/A	Fall
3I	0307	428	10/28/07	4	19174	4471	Fall
3J	0046	428	2/25/08	0	19375	910	Winter
3J	0307	428	3/14/08	0	15661	8106	Winter
3K	0046	428	10/12/08	1	15763	1135	Fall
2D	0307	429	12/9/08	0	4600	N/A	Fall
2E	0046	429	3/17/09	0	3500	N/A	Winter
2E	0307	429	4/3/09	0	1400	N/A	Spring

Table 1. Column 1 contains the alphanumeric ID of each operations period where the number refers to the laser in use and the letter refers to the sequence (note that Laser 2’s use was discontinued after 2C due to low energy output but was reactivated after Laser 3’s failure on 19 October, 2008, 2D completed the 3K track pattern); Column 2 has the Track numbers that cross Drangajökull have 4 digit IDs to distinguish these profiles from the 3-digit tracks used during ICESat 8-day patterns in 2003; Column 3 has the Release number of the GLA06 data used where the first digit describes the pointing refinement (higher is more reliable, some 5’s are now available) and the latter two digits refers to the level of processing system refinement (28 was the best available in 2008); Column 4 has the date of each profile over Drangajökull; Column 5 records the number of shots (and maximum number of elevation differences) over the ice cap’s DEM area; Columns 6 and 7 contain the local mean ICESat laser transmit and received energy values (where available, the variability in the received energy compared to the declining laser energy gives an indication of atmospheric conditions); Column 8 has the northern hemisphere season (used to guide season-to-season matches, note 3H in Mar./Apr. 2007, was early relative to other ‘spring’ operations).

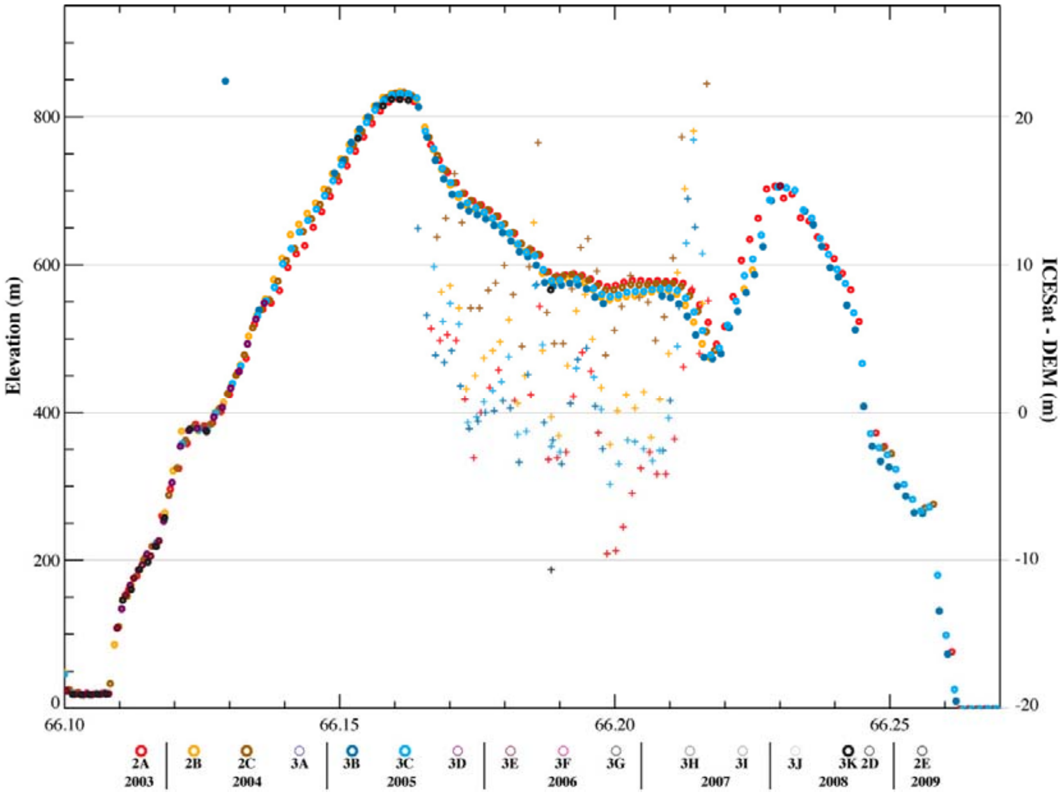

Figure 3a. Comparison of fifteen ICESat Track 0046 geoid-corrected elevation profiles across Drangajökull from late 2003 (Laser 2A) to early 2009 (Laser 2E) as colored dots. Profiles with data over the DEM have bolder dots on the time scale. Elevation differences from interpolated DEM grid cells have more scatter and are shown as colored pluses; their location indicates where the ice cap's DEM is situated. The left axis is for the ICESat elevations and the right axis is for the ICESat-DEM elevation differences. A 'high-cloud' ICESat elevation (3B) stands out at about 850 m above the rest of the topography (at left) and all such elevations have been removed from this analysis. Vertical exaggeration is about 15X.

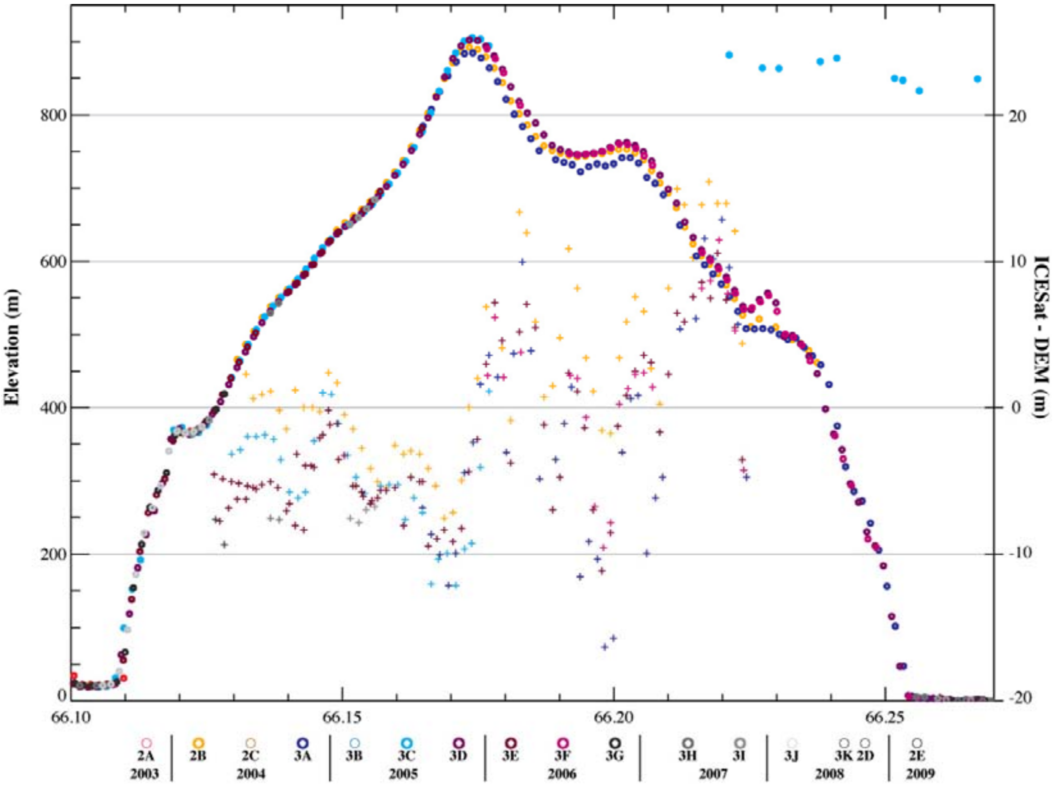

Figure 3b. Comparison of fifteen ICESat Track 0307 geoid-corrected elevation profiles across Drangajökull from late 2003 (Laser 2A) to early 2009 (Laser 2E) as colored dots. Profiles with data over the DEM have bolder dots on the time scale. Elevation differences from interpolated DEM grid cells have more scatter and are shown as colored pluses; their location indicates where the ice cap's DEM is situated. The left axis is for the ICESat elevations and the right axis is for the ICESat-DEM elevation differences. Multiple 'high-cloud' ICESat elevations (3C) stand out at about 850 to 900 m above the rest of the topography (at right) and all such elevations have been removed from this analysis. Vertical exaggeration is about 15X.

DATA DESCRIPTION

The primary objective of the study was to assess observed changes in the topography of Drangajökull using two ICESat altimetry 'repeat tracks' that were acquired up to 15 times during 2003–2009. To provide an independent baseline on the ice cap elevation, a digital elevation model (DEM) created from a ground-based GPS data set acquired 19-20 April 2005 enabled a quantitative assessment of the available ICESat altimetry data. The DEM was derived from geodetic GPS devices mounted on four snowmobiles that acquired data during two days of fieldwork. The GPS data were obtained along profiles spaced approximately every 350 m and oriented generally parallel to the long axis of the ice cap. Elevations were acquired every 20 m along these ground tracks and the data have a crossover error at intersecting tracks of approximately 1 m (J.F. Jónsdóttir, written comm., 2006). A GPS base station was operated in Skjaldfannardalur, Vestfirðir, during the survey of Drangajökull. The resulting data were gridded at 50 m, and a contour map of the ice cap was produced using ArcGIS software (Figure 2) that is referenced to the WGS-84 geoid (World Geodetic System). The GPS measurements that were used to make the DEM of Drangajökull were then geoid-corrected to mean sea level using a gravity map of Iceland produced by Gunnar Þorbergsson et al. (1993). For the purpose of these comparisons, the DEM is assumed to be an accurate topographic representation of the ice cap on 19-20 April 2005 but it may still have accuracy issues as discussed later.

ICESat repeat-elevation profiles over the northwestern half of Drangajökull are from two 91-day repeat tracks (0046 and 0307) that were profiled during 2003-2009 (Figure 3a, b; Table 1) up to 3 times a year. Four digit track numbers distinguish these 91-day tracks from 8-day repeat tracks (i.e., in ~8 days, ICESat would being the pattern again) acquired only in 2003. Laser pulses are transmitted at 40 Hz (40 shots per second) along all ICESat ground tracks. Depending on cloud cover, this produces an elevation every ~170 m from a 'footprint' designed to be ~70 m in diameter on the Earth's surface but which varied considerably in size during ICESat various operational periods (see http://nsidc.org/data/icesat/laser_op_periods.html - table of attributes). If the sky is clear, a precision of a few cm and a relative accuracy of about 20 cm for low-slope (< 0.25°) surfaces can be obtained (Shuman et al., 2006). However, laser-transmit energy of the Geoscience Laser Altimeter System (GLAS) that is ICESat's primary sensor has decreased with time and this has substantially impacted net retrieval of elevation data (Table 1 and Figure 3); note that declining energy has also reduced received laser pulses that can cause detector saturation and can impact derived elevations (Sun et al., 2004). A saturation correction algorithm has been developed to correct this problem and is available in the Release 428/429 data (see explanation at http://nsidc.org/data/icesat/yxx_release_numbers.html) explored here but its results are a few decimeters in most cases and are accurate only over slopes less than 1°, so these corrections were not applied to the Drangajökull data (~10% of elevations in higher energy operations periods have saturated returns, see Table 1). Because of small, time-varying, orbit-ephemeris errors, on-board instrument performance, and (or) incomplete knowledge of laser pointing (Schutz et al, 2005), 'repeat track' altimetry data may diverge by 100 m or more from the intended ground track (Figure 2, note cross-track spacing of shots from successive repeats as well as gaps due to cloud cover). Over typical ice-cap or outlet-glacier slopes (~5°), these spatial track offsets can lead to substantial elevation variations so that 'repeat elevations' are difficult to compare directly for elevation-change assessments.

This study evaluates ICESat repeat profile accuracy relative to the well-described and nearly instantaneous (obtained in ~2 days) ice cap surface elevation DEM. In particular, the DEM's ability to enable comparisons of ICESat repeat tracks that are spread across the ice cap will be assessed. After significant residual clouds have been identified and removed through a technique detailed in the following section, the remaining 'cloud-cleared' ICESat data are used to derive a multi-year time series of elevation changes relative to the Drangajökull DEM. These satellite-based results are then compared with multi-year mass balance studies done by more traditional (stake re-measurement and area extrapolation) techniques (see Figure 2). The ability of analyses such as this to detect changes should represent a validation of the ICESat mission.]

METHODOLOGY

To assess elevation differences during the period 2003 to 2009 between the ICESat profiles and the April 2005 DEM, it was necessary to remove erroneous elevations from 'high cloud' reflections. The frequent cloud cover that is typical of northwestern Iceland (Figure 1) can impact each of the laser altimetry profiles across Drangajökull. For example, clouds can cause gaps within or the total loss of a laser profile of interest, or in some cases here, a laser pulse from a cloud top can be strong enough to be detected as a 'surface' in the GLAS automated processing routine (Figure. 3a, b, note 'high clouds', profile gaps as well as several repeats with no elevation data whatsoever). These erroneous elevations may occur in any profile and were assessed using a 'stacked profile technique' for Track 0046 and Track 0307. The 'stacking' procedure utilizes a 40 Hz version of the reference track and matches each elevation value to its closest reference track location. The mean elevations for each 40 Hz point are then calculated and values that are higher than some threshold above the mean (70 m in this study) for that 40 Hz reference track location are identified and removed from further study. As noted above, clouds in this area, such as cirrus, can impact multiple ICESat repeats (see Table 1). To account for this, the means are recalculated based on the data retained after the first step and further points above the threshold, if any, are identified and removed until no more points are excluded. This procedure was used to show the locations of all ‘good shots’ in Figure 2. The 70-m threshold used to detect ‘high clouds’ is adjustable and somewhat arbitrary; it depends on the steepness of the topography sampled by ICESat’s discrete footprints and flatter topography could use a smaller threshold. Practical application is fairly simple and the process can clearly remove erroneous data (see Figure 3b, other known high cloud returns would plot off the y axis range used in Figure 3).

However, this cloud-clearing approach does not yet account for smaller elevation impacts due to thinner clouds or other phenomena such as ground fog or blowing snow that delay but do not cause very large incorrect elevations. Atmospheric conditions can cause laser altimeter elevations to be close to the real topographic elevation but actually too low (below the true elevation of the ice cap at that time) due to scattering as the laser pulses pass down and back through the atmosphere thus causing a longer travel time usually at the 10s of cm to m level (Spinhirne et al., 2005). However, as illustrated in Figure 3, the magnitude of the cloud impacts should be small relative to ICESat-DEM differences derived from the GLA06 elevation data used in this study and were thus simply accepted within the overall uncertainty. To calculate these elevation differences, the four DEM grid values adjacent to each ‘good’ ICESat elevation value’s location were interpolated to the same latitude/longitude position. See discussion of the different Geoscience Laser Altimeter (GLA) data sets in Schutz et al. (2005). All data used in this study are from GLA06 (GLAS/ICESat L1B Global Elevation Data, see description at http://nsidc.org/data/gla06.html). The ICESat elevations are referenced to the Topex/Poseidon ellipsoid and were geoid corrected using the geopotential model EGM96 in Release 428/429 before all elevation differences were calculated. As noted previously, the WGS84-referenced GPS measurements that were used to make the DEM of Drangajökull were geoid-corrected to mean sea level using a gravity map produced by Þorbergsson and others (1993), so some uncertainty in the elevation differences shown in Figure 3 may be due to the use of differing reference ellipsoids, the need to translate between them, as well as the different geoid corrections used (see additional discussion below).

As an independent check on the altimetry analysis, a series of stakes was established in 2004 and re-measured and replaced as needed seasonally until 2007. The winter mass balance is measured at about 15 points along the long axis of the glacier. The summer balance is only measured at about 3-5 stakes (some stakes were lost due to melting) and these data were extrapolated and interpolated according to experience by Sigurðsson. As part of the fieldwork, the position of the equilibrium line and whether it passes the firn line is noted. This indicates qualitatively whether the glacier had a positive or negative mass balance each year. The fall visits to the glacier were somewhat problematic and in one case measurements were not conducted until 17 December, (2006). By that time some of the stakes were snowed over so the values for 2006/2007 are less certain. That is the main reason for not finding the stakes in the fall, sufficient accumulation to bury the stake positions. All stakes are reestablished every spring, usually in April/May. The two top stakes near Jökulbunga are the most problematic to find in the fall. The summer-balance values for those buried stakes is estimated by extrapolation and experience from measurements on other glaciers in Iceland that have been repeatedly surveyed by INEA personnel. Additional winter-balance points were acquired along the northwest stake line from the very snout of the outlet glacier to the firn line at about 500-600 m elevation. The results for 2004/2005 (in mm w.e.) are 1930 for the winter balance, -1620 for the summer balance, and 310 for the net balance year. For 2005/2006, the same values are 2870, -2810, and 60 and for 2006/2007, they are 2960, -2690, and 270 respectively. So, despite longer-term mass loss, Drangajökull appears to have some recent years of positive to clearly positive mass balance.

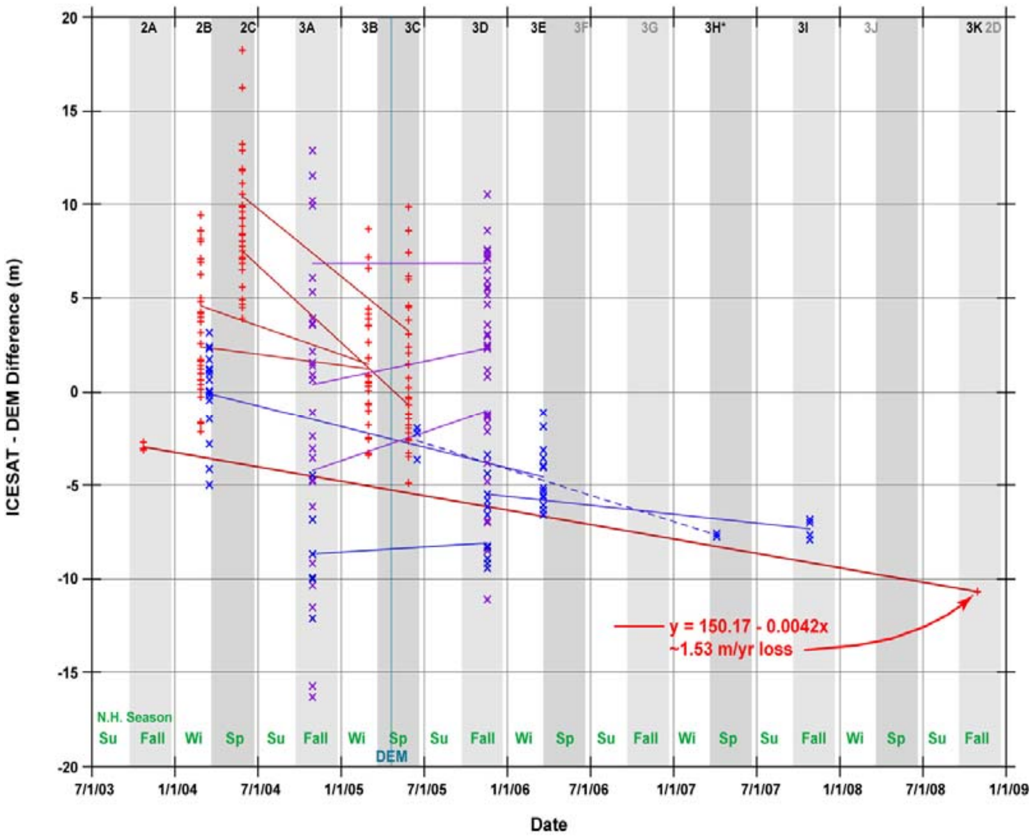

Figure 4. Illustration of the time series of ICESat-DEM elevation differences from late 2003 to late 2008 (no data was available in early 2009 Laser 2E operations, see Table 1). All trends are determined from ‘same track, same season, same elevation range’ data subsets. The 0046 data and trends are shown in red (pluses) and the 0307 data and trends are shown in blue for the south facing portion of the ice cap or purple if from the NE facing slope (x’s). The thin blue vertical line shows the date of the DEM acquisition (19-20 April 2005). Alternating white and grey vertical bars indicate northern hemisphere seasons and ICESat operations periods are indicated (grey-labeled operations periods had no ‘same season and same elevation’ data to compare). Substantial ICESat elevation data were acquired from 2003 to 2005; only very limited data is available after early 2006 (see Table 1). The linear regression from 2A to 3K offers the longest time interval and has been converted to an annual elevation loss but is based on limited data (discussed further in the text).

RESULTS AND DISCUSSION

Our analysis was impacted by factors that challenge accurate determination of ice-cap surface elevations from ICESat repeat track data and, consequently, assessment of Drangajökull’s elevation trends. First, ICESat tracks and/or crossovers (an intersection of an ascending and descending track that enables consistency checks on ICESat's overall performance) may not be over or within the area of interest or may not sufficiently sample the area (see crossover and available altimetry locations in Figure 2). Second, cloud cover may cause obvious errors in the retrieved altimetry data or may obscure part or all of the target during an ICESat overpass (Figure 3). Third, examination of the elevation differences between the ICESat passes (when/where available) and the DEM indicate large and seemingly slope-dependent offsets (see Figure 3, elevation differences). And fourth, ICESat’s ‘repeat tracks’ (2 to 3 times a year during 2003-2009) do not consistently profile the same terrain (see spread of points for each track in Figure 2) along the targeted reference track making it difficult to derive a elevation change time series that accounts for accumulation, melt, densification, and other seasonal factors that can influence an ice cap's elevation.

The Drangajökull DEM, derived from GPS ground surveys in April 2005, enables a fairly thorough evaluation of all these factors (Figure 3a, b and Figure 4) and their effective influence on elevation change and mass balance trends. As previously noted, the GPS data were derived from data collected at fairly high resolution and then gridded at 50 m resolution to make the DEM by INEA personnel. To calculate elevation differences from each available altimetry measurement, the four closest elevations were then interpolated to match ICESat's laser footprint locations. DEM slopes along Tracks 0046 and 0307 range from a few degrees to more than 10 degrees and the apparent recurring relationship between slope and elevation differences suggests that there is a geolocation error (or at least an offset) between the two data types. For example, if ICESat locations relative to the DEM are off by several 10s of meters in the maximum slope direction, this would produce elevation differences of the observed magnitude (see Figure 4) and they will vary in proportion to the terrain slope (see Figure 3).

To test this, ICESat elevations were converted to a WGS-84 reference basis and geoid corrected. Then each point in an ICESat profile was shifted in 10 m increments in latitude and longitude across the DEM. For each 10 m step, the standard deviation of the elevation differences for all the points in the profile was computed. Then a 'best fit' XY offset between the two data sets was defined when the standard deviation of the differences reached a minimum. Due to insufficient data across the DEM for some repeats, not every profile could be used and even for the more complete passes, no consistent XY offset was determined for Release 428 data. However, the ICESat data appear to be offset 10 to 30 m east relative to the DEM and an inconsistent but smaller amount north or south using the available, more complete, ICESat 0047 and 0307 passes. Even after these optimized adjustments, elevation differences can still range over nearly many meters (~8 meters total for the two 0047 passes taken closest to when the GPS information was acquired) suggesting that this issue is not fully resolved. Currently, only unpublished assessments of ICESat's positioning knowledge and accuracy are available. The values that are available are means and standard deviations of the full operations period analyses and so may not represent a particular ICESat track in an operations period over an independent elevation assessment (again see http://nsidc.org/data/icesat/laser_op_periods.html - table of attributes). In addition, the mean elevation difference between the DEM and the 3B and 3C 0046 ICESat elevations that were just before and just after ground-based GPS profiling (~50 days before and ~40 days after, respectively, see Table 1) are both close to 1 m with 3 to 4 m standard deviations (the ICESat elevations are above the DEM in both cases, see Figure 4) suggesting there may be a static offset between the two data sets after correcting them to the same ellipsoid and geoid-corrected basis.

Despite these uncertainties, using the DEM as a static reference surface is necessary to examine trends in the available elevations from Tracks 0046 and Track 0307 (Figure 4) for several reasons. Use of the DEM enables the cross-track slope and any resulting elevation difference between repeat passes due to ice cap topography to be accounted for (e.g., for 3A and 3D repeats of Track 0307, the 3D pass is ~200 m upslope and perhaps ~20 m above the 3A pass, see Figure 2 north of 'h' (Jökulbunga) and similar latitudes on Figure 3b). In addition, because the topography along the ICESat profiles was usually irregularly sampled due to clouds (including some tracks with no altimetry returns over the DEM, see Table 1), the DEM topography allows the available ICESat – DEM elevation differences to be consistently segregated by elevation range. This enables lower elevation data to be examined separately from changes from higher elevations (see Figure 3a and b for the elevation ranges observed by the two tracks). For similar reasons, the Track 0307 data was separated into north of the ice cap summit (Jökulbunga or 'h', see Figure 2) and south of the summit. This enables south-facing and northeast-facing slope data to be compared independently. In all cases for both tracks, the elevation differences shown in Figure 4 are also segregated by season (all trends are only from same season elevation differences).

With these challenges, especially the dramatic reduction in elevation returns from ICESat as laser transmit energy dropped close to 30 mJ in 2006 (see Figure 4 and Table 1), an overall elevation loss trend can be estimated for 2003-2008 (no data is yet available in 2009 over the ice cap's DEM). Because very few same track, same season, same elevation range data are available from Track 0046 or 0307 over the 2003-2009 time period, the longest elevation trend available is used to estimate the possible net elevation loss. The very limited amount of 2A to 3K data from Track 0047 suggests that elevation changes >1.5 m a^{-1} may be evident on the west-facing slope of Drangajökull from late 2003 to late 2008. Although this is within the possible range of losses for this part of Iceland, the outlet glacier being sampled (Leirufjarðarjökull) has been known to surge prior to 2003 (Sigurðsson, 2003) and so the observed Track 0046 elevation losses may be related to dynamic movement, not simply melt and/or ablation. From inspection of Figure 4, there are few multi-year trends derived from the same-season, same-elevation data. The fact that the shorter trends available from Track 0307 (2B to 3E, 3C to 3H, and 3D to 3I, all south facing) have generally the same slope as the longer 0047 trend suggests that the net loss on Leirufjarðarjökull may reasonably represent the west and south facing aspects of the ice cap.

In addition to these challenges, it is also clear from inspection of Figure 4 that it is difficult to resolve seasonal variations although single year elevation gains (Track 0307 3A to 3D trends) and more substantial elevation losses (Track 0047 2C to 3C) both exist suggesting that elevations do vary through the year due to natural processes (e.g., Ólafsson et al., 2007) and can be observed within the limited ICESat data. The Track 0307 3A to 3D comparison is the most complex, because it is the only pair of passes that is from the same season and that is substantially complete; this enables subsetting the data into common elevation ranges both north (purple points) and south (blue points) of the summit location. The south-facing data are similar to the northeast facing data but the northeast-facing data have somewhat larger elevation increases. The 3A to 3D comparisons show the only positive elevation trends (fall 2004 to fall 2005) and this compares favorably to the largest positive net mass balance measured in the field (310 mm w.e.). Unfortunately, as might be expected, there is nothing to suggest from this pair of tracks that elevation differences vary consistently with increasing elevation up to the summit. This suggests that the flat to slightly increasing elevations during this time frame may be due to the spatial distribution and/or timing of snowfall during a time period of relatively higher accumulation in 2005 (Ólafsson et al., 2007). Additional work at Drangajökull along the two ICESat profiles at least, on the ground or possibly from an airborne swath laser altimeter would greatly aid evaluation of the ICESat-DEM differences as would additional clear ICESat passes.

CONCLUSIONS

Our analysis shows that ICESat repeat altimetry data can be used over smaller ice caps with fairly steep topography to derive elevation differences when augmented with a GPS-derived DEM. Although there are substantial challenges simply in comparing the ICESat elevations to the DEM, these ICESat-DEM differences have enough consistency that it appears possible to derive elevation-change trends. For Drangajökull however, it is not clear that those results are compatible with more traditional mass-balance assessments possibly due to the relatively small portion of the ice cap that is profiled. Overall, the analysis indicates that there are significant challenges in measuring ice-cap surface elevations and especially elevation changes from ICESat data alone through cloudy skies or over sloping and irregular or rough terrain (e.g., Thomas et al., 2006). It should be noted that the small number of complete profiles throughout the years of ICESat's operations makes it very difficult to assess elevation changes through time by any technique. This may help explain the overall difference of the altimetry analysis and the traditional mass balance approach of re-measuring stakes.

The problem of ‘high-cloud’ elevations can be addressed by using multiple repeats of a single track via the ‘stacking’ threshold technique discussed here. For larger areas, this would need to be done in an automated fashion. Also, this approach cannot be applied to ‘single profile’ data such as off-nadir ICESat tracks or those taken only once, e.g., in early 2A operations, and it does not address more subtle cloud impacts that cause elevation values to be too low on a shot-by-shot basis. A reliable 40 Hz cloud characterization would be needed to characterize small elevation errors for Drangajökull but these impacts appear to be dominated by other issues that are not fully resolved such as static offsets in geoid corrected elevations.

In this study, we have demonstrated that change-detection analyses need to integrate the latest available ICESat data relative to well-constrained elevations as this serves to constrain remaining uncertainties in ICESat laser pointing and ranging knowledge. In addition, ICESat repeat-track, change-detection results must account for variable cross-track distances as well as the underlying slope magnitudes and directions to achieve the most accurate results. The spread of these repeat track locations, with consequently offset footprint spacing when not obscured by clouds, and severe to subtle cloud-related elevation impacts all act to decrease absolute elevation knowledge and thus decrease elevation change uncertainty. ICESat is clearly observing the underlying ice cap target's topography (see Figure 3) but faces a number of challenges before it can confidently assess ice elevation change and mass balance.

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