Inter-annual surface evolution of an Antarctic blue-ice moraine using multi-temporal DEMs

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Abstract

Multi-temporal and fine resolution topographic data products are increasingly used to quantify surface elevation change in glacial environments. In this study, we employ 3D digital elevation model (DEM) differencing to quantify the topographic evolution of a blue-ice moraine complex in front of Patriot Hills, Heritage Range, Antarctica. Terrestrial laser scanning (TLS) was used to acquire multiple topographic datasets of the moraine surface at the beginning and end of the austral summer season in 2012/2013 and during a resurvey field campaign in 2014. A complementary topographic dataset was acquired at the end of season 1 through the application of Structure-from-Motion with multi-view stereo (SfM-MVS) photogrammetry to a set of aerial photographs acquired from an unmanned aerial vehicle (UAV). Three-dimensional cloud-to-cloud differencing was undertaken using the Multiscale Model to Model Cloud Comparison (M3C2) algorithm. DEM differencing revealed net uplift and lateral movement of the moraine crests within season 1 (mean uplift ~0.10 m), and surface lowering of a similar magnitude in some inter-moraine depressions and close to the current ice margin, although we are unable to validate the latter. Our results indicate net uplift across the site between seasons 1 and 2 (mean 0.07 m). This research demonstrates that it is possible to detect dynamic surface topographical change across glacial moraines over short (annual to intra-annual) timescales through the acquisition and differencing of fine-resolution topographic datasets. Such data offer new opportunities to understand the process linkages between surface ablation, ice flow, and debris supply within moraine ice.

1. Introduction

Fine-resolution topographic data products are now routinely used for the geomorphometric characterisation of Earth surface landforms (e.g. Passalacqua et al., 2014, 2015; Tarolli, 2014). Recent decades have seen the advent and uptake of a range of surveying technologies for characterising the form and evolution of Earth surface topography at the macro- (landscape; kilometres), meso- (landform; metres) and micro-scales (patch-scale; centimetre-millimetre). These technologies have included, amongst others, the use of satellite remote sensing techniques (e.g. Kääb, 2002; Smith et al., 2006; Farr et al., 2007; Stumpf, 2014; Noh and Howat, 2015), as well as field-based surveying platforms such as electronic distance meters (total station; e.g. Keim et al., 1999; Fuller et al., 2003), differential global positioning systems (dGPS; e.g. Brasington et al., 2000; Wheaton et al., 2010), terrestrial laser scanning (TLS; e.g. Rosser et al., 2005; Hodge et al., 2009), airborne light detection and ranging (LiDAR; e.g. Bollmann et al., 2011) and softcopy or digital photogrammetry (e.g. Micheletti et al., 2015).

More recently, geoscientists are increasingly adopting low-cost Structure-from-Motion with multi-view stereo (SfM-MVS) methods, which employ computer vision and multi-view photogrammetry techniques to recover surface topography using optical (e.g. James and Robson, 2012; Westoby et al., 2012; Javernick et al., 2014; Micheletti et al., 2014; Woodget et al., 2015; Smith and Vericat, 2015) or thermal imagery (e.g. Lewis et al., 2015). Concomitant developments in lightweight unmanned aerial vehicle (UAV) technology, specifically decreasing system costs, increased portability, and improvements in the accessibility of flight planning software have encouraged the acquisition of repeat, fine-resolution (metre to centimetre) topographic data products from low-altitude aerial photography platforms (e.g. Niethammer et al., 2010; Ouédraogo et al., 2014; Bhardwaj et al., 2016). Furthermore, the differencing of topographic datasets acquired at different times is now an established method for quantifying the transfer of mass and energy through landscapes at the spatial scales of observation at which many processes operate (Passalacqua et al., 2015).

Fine-resolution topographic datasets produced using airborne or ground-based light detection and ranging (LiDAR), or terrestrial or low-altitude aerial digital photogrammetry have been used for a diverse range of applications in various glacial, proglacial, and periglacial environments at a range of scales, including: the quantification of ice surface evolution (e.g. Baltsavias et al., 2001; Pitkänen and Kajuutti, 2004; Keutterling and Thomas, 2006; Schwalbe and Maas, 2009;

79 Immerzeel et al., 2014; Pepin et al., 2014; Whitehead et al., 2014; Gabbud et al.,
80 2015; Kraaijenbrink et al., 2015; Piermattei et al., 2015; Ryan et al., 2015); mapping
81 the redistribution of proglacial sediment (e.g. Milan et al., 2007; Irvine-Fynn et al.,
82 2011; Dunning et al., 2013; Staines et al., 2015) and moraine development
83 (Chandler et al., 2015); the characterisation of glacier surface roughness (e.g. Sanz-
84 Ablanedo et al., 2012; Irvine-Fynn et al., 2014), glacial sedimentology (Westoby et
85 al., 2015), and hydrology (Rippin et al., 2015); as well as input data for surface
86 energy balance modelling (e.g. Arnold et al., 2006; Reid et al., 2012); and for
87 characterising glacial landforms in formerly glaciated landscapes (e.g. Smith et al.,
88 2009; Tonkin et al., 2014; Hardt et al., 2015).
89
90 In this study, we utilise fine-resolution topographic datasets to quantify the surface
91 evolution of a blue-ice moraine complex in a remote part of Antarctica. Blue-ice
92 areas cover approximately 1% of Antarctica's surface area (Bintanja, 1999), yet they
93 remain relatively understudied. Relict blue-ice moraines preserved on nunataks are
94 key indicators of ice sheet elevation changes; however, limited data exist on rates
95 and patterns of surface reorganisation, which may be of use for contextualising the
96 results of, for example, cosmogenic nuclide dating and geomorphological mapping
97 (Hein et al., 2016). This research seeks to quantify the short-term surface evolution
98 of a moraine complex in Patriot Hills, Heritage Range, Antarctica (Fig. 1), through the
99 differencing and analysis of multi-temporal topographic datasets acquired using TLS
100 and the application of SfM-MVS photogrammetry to optical imagery acquired from a
101 low-altitude UAV sortie.
102
103 **2. Study site**
104
105 The study site is a blue-ice moraine complex, located on the northern flank of the
106 Patriot Hills massif at the southern-most extent of Heritage Range, West Antarctica
107 (Fig. 1). Blue-ice moraine formation is hypothesised to be the result of preferential
108 ablation of marginal ice by katabatic winds, which in turns prompts the modification
109 of ice flow and englacial sediment transport pathways such that basal sediment is
110 brought to the ice surface, where it is deposited (e.g. Bintanja, 1999; Sinisalo and
111 Moore, 2010; Fogwill et al., 2012; Spaulding et al., 2012; Hein et al., 2016). The site
112 comprises a series of broadly east-west oriented moraine ridges and inter-moraine
113 troughs, as well as an area of subdued moraine topography immediately adjacent to
114 the ice margin (Fig. 2). At this location, the active blue-ice moraines occupy an
115 altitudinal range of 60-70 m above the ice margin (~730 m a.s.l.) and extend for a
116 distance of up to 350 m into a bedrock embayment (Fig. 1). The blue-ice moraines
117 can be traced for a distance of >4 km to the east and north-east, parallel to the range

118 front, and fill ice-marginal embayments. The site is geomorphologically and
119 sedimentologically complex (e.g. Vieira et al., 2012; Westoby et al., 2015), and,
120 along with moraine ridges and troughs, includes areas of subdued ice-marginal
121 topography with thermokarst melt ponds, local gullying and crevassing on ice-
122 proximal and distal moraine flanks, as well as solifluction deposits at the base of the
123 surrounding hillslopes. The bedrock hillslopes are overlain by a till drape with rare,
124 large exotic sandstone boulder erratics which have some evidence of periglacial
125 reworking. Field observations suggest that the blue-ice moraines are dynamic
126 features which are undergoing localised surface changes. It is these short-term,
127 changes which are the subject of investigation in this paper.
128
129 **3.   Methods and data products**
130
131 This research employs two methods for reconstructing moraine surface topography,
132 specifically TLS and SfM-MVS photogrammetry. Two field campaigns at Patriot Hills
133 were undertaken with a 12-month survey interval. Briefly, TLS data were acquired at
134 the beginning and end of austral summer season 1 (December 2012 and January
135 2013, respectively), and in a short resurvey visit in season 2 (January 2014). Low-
136 altitude aerial optical photography was acquired from a UAV at the end of season 1
137 and was used as the primary input to SfM-MVS processing. The following sections
138 detail the two methods of topographic data acquisition, data processing, and
139 subsequent analysis using cloud-to-cloud differencing.
140
141 **3.1.   Topographic data acquisition**
142
143 **3.1.1. Terrestrial Laser Scanning**
144
145 TLS data were acquired using a Riegl LMS-Z620 time-of-flight laser scanner, set to
146 acquire ~11,000 points per second in the near-infrared band at horizontal and
147 vertical scanning increments of 0.031°, equivalent to a point spacing of 0.05 m at a
148 distance of 100 m and with a beam divergence of 15 mm per 100 m. Data were
149 acquired from six locations across the site at the beginning of season 1 (7th -11th
150 December 2012; Fig. 1; Table 1). Two of these positions were re-occupied at the
151 end of season 1 (9th January 2013) and three positions were reoccupied in season 2
152 (Fig. 1; 14th January 2014). Following manual editing and the automated removal of
153 isolated points to improve data quality, each set of scans were co-registered in Riegl
154 RiSCAN PRO software (v. 1.5.9) using a two-step procedure employing coarse
155 manual point-matching followed by the application of a linear, iterative, least-squares
156 minimisation solution to reduce residual alignment error. Individual scans were then

157 merged to produce a single 3D point cloud for each scan date. Merged scan data
158 from the end of seasons 1 and 2 were subsequently registered to the scan data from
159 the beginning of season 1 using the methods described above (Table 1).
160
3.1.2. Structure-from-Motion with multi-view stereo photogrammetry
162
163 Low-altitude aerial photographs of the study site were acquired using a 10-Megapixel
164 Panasonic Lumix DMC-LX5 compact digital camera with a fixed focal length (8 mm)
165 and automatic exposure settings, mounted in a fixed, downward-facing (nadir)
166 perspective on a sub-5 kg fixed-wing UAV. Photographs were acquired in a single
167 sortie lasting ~5 minutes. A total of 155 photographs were acquired at a 2-second
168 interval at an approximate ground height of 120 m, producing an average image
169 overlap of 80%, and an approximate ground resolution of 0.07 m^2 per pixel. Mean
170 point density was ~300 points per m^2, compared to a mean of 278 points per m^2 for
171 the TLS datasets. Motion blur of the input images was negligible due to favourable
172 image exposure conditions and an appropriate UAV flying height and speed.
173
174 UAV photographs were used as input to SfM reconstruction using the proprietary
175 Agisoft PhotoScan Professional Edition (v. 1.1.6) software. Unique image tie-points
176 which are stable under variations in view perspective and lighting are identified and
177 matched across input photographs, similar to Lowe's (2004) Scale Invariant Feature
178 Transform (SIFT) method. An iterative bundle adjustment algorithm is used to solve
179 for internal and external camera orientation parameters and produce a sparse 3D
180 point cloud. The results of the first-pass camera pose estimation were scrutinised
181 and only 3D points which appear in a minimum of 3 photographs and possessed a
182 reprojection error of <1.0 were retained. A two-phase method of UAV-SfM data
183 registration was employed: 1) ground control was obtained by identifying common
184 features in the UAV-SfM photographs and TLS data from the end of season 1
185 (acquired 4 days after the SfM data; Table 1), such as the corners of large, well-
186 resolved boulders or bedrock outcrops. GCP data were used to optimise the initial
187 camera alignment and transform the regenerated UAV-SfM data to the same object
188 space as the TLS data, producing an *xyz* RMS error of 0.23 m. 2) following dense
189 reconstruction using Multi-View Stereo methods, 3D point data were exported to
190 RiSCAN PRO (v. 1.5.9) software, and a linear, iterative, least-squares minimisation
191 employing surface plane matching was used to improve the alignment and reduce
192 the *xyz* RMS error to 0.03 m.
193
3.2. Cloud-to-cloud differencing
195

196 Three-dimensional cloud-to-cloud distance calculations were used to quantify
197 moraine surface evolution (e.g. Lague et al., 2013). Since the dominant direction of
198 surface evolution across the study site was unknown *a priori*, the application of an
199 algorithm that is capable of detecting fully three-dimensional topographic change
200 was deemed to be the most appropriate method in this context. To this end, we
201 employ the Multiscale Model to Model Cloud Comparison (M3C2) algorithm (Lague
202 et al., 2013; Barnhart and Crosby, 2013), implemented in the open-source
203 CloudCompare software (v. 2.6.1) for change detection.

204

205 The M3C2 algorithm implements two main processing steps to calculate 3D change
206 between two point clouds: 1) estimation of surface normal orientation at a scale
207 consistent with local surface roughness, and 2) quantification of the mean cloud-to-
208 cloud distance (i.e. surface change) along the normal direction (or orthogonal
209 vector), which includes an explicit calculation of the local confidence interval. A point-
210 specific normal vector is calculated by fitting a plane to neighbouring 3D points that
211 are contained within a user-specified search radius. To avoid the fluctuation of
212 normal vector orientations and a potential overestimation of the distance between
213 two point clouds, the radius, or scale, used for normal calculation needs to be larger
214 than the topographic roughness, which is calculated as the standard deviation of
215 local surface elevations (σ). The orientation of the surface normal around a point, *i*, is
216 therefore dependent on the scale at which it is computed (Lague et al., 2013). A trial-
217 and-error approach was employed to reduce the estimated normal error, $E_{norm}(\%)$,
218 through refinement of a re-scaled measure of D, ξ, where:

219

220 $$\xi(i) = \frac{D}{\sigma_i(D)}$$ Eq. (1)

221

222 Using this re-scaled measure of D, ξ can be used as an indicator of estimated normal
223 orientation accuracy, such that where ξ falls in the range ~20-25, the estimated
224 normal error is $E_{norm} < 2\%$ (Lague et al., 2013). A fixed normal scaling of 2 m was
225 found to be sufficient to ensure that $\xi > 20$ for >98% of points in each topographic
226 dataset.

227

228 The radius of the projection cylinder, *d*, within which the average surface elevation of
229 each cloud is calculated, was specified as 2 m. This scaling ensured that the number
230 of points sampled in each cloud was ≥30, following guidance provided by Lague et
231 al. (2013). M3C2 execution took ~0.3 h for each differencing task on a desktop
232 computer operating with 32 GB of RAM, and a 3.4 GHz CPU. Cloud-to-cloud
233 distances and statistics were projected onto the original point cloud. M3C2 output

was subsequently masked to exclude points where change is lower than level of detection threshold for a 95% confidence level, $LoD_{95\%}(d)$, which is defined as:

$$LoD_{95\%}(d) = \pm 1.96 \left(\frac{\sigma_1(d)^2}{n_1} + \frac{\sigma_2(d)^2}{n_2} + reg \right)$$ Eq. (2)

where d is the radius of the projection cylinder, reg is the user-specified registration error, for which we substitute the propagated root mean square alignment error for point clouds n_1 and n_2 (Table 2; Eq. (1)) and assume that this error is isotropic and spatially uniform across the dataset.

To calculate the total propagated error for each differencing epoch, σ_{DoD}, the estimates of errors in each point cloud (i.e. the sum of the average scan-scan RMS error and a project-project RMS error, where applicable) were combined using:

$$\sigma_{DoD} = \sqrt{\sigma_{C_1}^2 + \sigma_{C_2}^2}$$ Eq. (3)

where $\sigma_{C_1}^2$ and $\sigma_{C_2}^2$ are the RMS errors associated with point clouds C_1 and C_2.

3.3. Data intercomparison: SfM vs. TLS

Whilst the UAV-SfM dataset acquired at the end of season 1 significantly improves on the spatial coverage afforded by the use of TLS across the moraine embayment, an analysis of the relative accuracy of the reconstructed surface topography of the former is required. To this end, Fig. 3 shows the results of vertical differencing of the UAV-SfM and TLS data and is complemented by a series of surface elevation profiles (Fig. 4). These results reveal that 83% of the UAV-SfM data are within ±0.1 m of the equivalent TLS data when gridded as the mean of vertical displacement in 10 m^2 grid cells.

However, two zones of substantial vertical discrepancy exist, namely the northernmost (ice-marginal) sector of the site, where the UAV-SfM data locally underestimate the equivalent TLS surface elevation by <-0.20 m (mean -0.13 m), and a zone to the north-west of the site, where the UAV-SfM data locally overestimate the TLS ground surface elevation by >0.20 m (mean 0.12 m). We propose two explanations for these vertical discrepancies. Firstly, it was difficult to identify corresponding features in the TLS and UAV-SfM datasets in the north-western sector of the site due to the sparsity of TLS data coverage here at the end of

272   season 1 (*cf.* Fig. 5c and Fig. 5d). Secondly, the UAV executed sharp banking turns
273   in this area of the site to clear a hillslope spur. These manoeuvres were difficult for
274   the on-board camera stabilising gimbal to compensate for, thereby reducing the
275   effective side- and forward overlap of the aerial photography, Similar banking turns
276   were carried out at the eastern edge of the site, however, it was possible to more
277   confidently identify GCPs in the TLS data in this region, which appears to have had a
278   mitigating effect against the effects of reduced image overlap on scene
279   reconstruction. Finally, those features that did appear in the TLS data in this sector
280   were typically near-vertical faces of large clasts which were oriented toward the
281   scanner, and which were not well-resolved in the UAV-SfM data due to its nadir
282   perspective. This made the accurate identification of matching clast features or
283   edges challenging. Ultimately, we attribute less confidence in both the geometric
284   accuracy of the 3D SfM-MVS reconstruction and final model-to-model alignment in
285   the north-western sector of the site.

287   We attribute underestimated UAV-SfM surface elevations in the centre-north of the
288   site to also be a product of the differing spatial extents of the two datasets. In this
289   location, the northernmost extent of the UAV-SfM data encompasses the entire ice-
290   marginal zone, whereas the equivalent TLS data were truncated at the foot of the
291   main moraine crest due to logistical constraints which precluded the acquisition of a
292   more complete TLS dataset at the end of season 1. Since no robust GCPs could be
293   identified in the TLS data for the ice-marginal zone for use in the UAV-SfM camera
294   optimisation and registration process, the ground surface geometry in this area tends
295   towards a systematic negative elevation bias, possibly as the result of residual radial
296   lens distortion following camera calibration in PhotoScan (e.g. James and Robson,
297   2014), we were unable to compensate for.

299   Transect data also highlight areas of inconsistency, specifically often considerable
300   offsets between the TLS and SfM data which were collected at the end of season 1
301   and which, in places, approach 0.5 m in magnitude (e.g. at ~27 m distance in profile
302   A, and between 22-30 m in profile B; Fig. 4). An additional explanation for these
303   inconsistencies could be the evolution of moraine surface topography in the 4-day
304   interval which separated the acquisition of the TLS and SfM data at the end of
305   season 1 (Table 1), with the implication that features used as GCPs in the TLS data
306   and their counterparts in the UAV-SfM data were not static, thereby affecting the
307   georeferencing and SfM optimisation solution. However, since we observed no
308   clustering of large GCP errors in areas of activity, as shown in the TLS-TLS
309   differencing results, this factor is unlikely to account for these topographic
310   inconsistencies.

311
312 Topographic mismatches between the TLS and UAV-SfM data also appear to be the
313 most prominent in areas of steep topography (Fig. 3; Fig. 4). These areas were
314 generally well-resolved in the TLS data (where not topographically occluded), but
315 may have been resolved in less detail and with less accuracy in the UAV-SfM data,
316 where the fixed camera angle promotes the foreshortening of these steep slopes in
317 the aerial photography. These differences might also be explained by the near-
318 parallel and largely nadir view directions of the UAV imagery, which represent a
319 'non-convergent' mode of photograph acquisition that has elsewhere been found to
320 result in the deformation, or 'doming' of SfM-derived surface topography (e.g. James
321 and Robson, 2014; Rosnell and Honkavaara, 2012; Javernick et al., 2014).
322
323 Model deformations can be countered to some degree through the inclusion of
324 additional, oblique imagery, and the use of a well-distributed and photo-visible GCP
325 network (James and Robson, 2014). However, although the latter were relatively
326 evenly distributed across our study site, the inclusion of these data and subsequent
327 use for the optimisation of the SfM data prior to dense point cloud reconstruction
328 does not appear to have altogether eliminated these model deformations. We
329 discuss the implications of data quality issues for interpreting geomorphological
330 process analysis in sections 4 and 5.
331
332 **4.   Short-term topographic evolution of blue-ice moraines**
333
334 **4.1. Vertical displacement**
335
336 The results of 3D cloud-to-cloud differencing are summarised in Figure 5. Threshold
337 levels of change detection ranged from 0.094 – 0.103 m. The upper (i.e. most
338 conservative) bound of this range was applied to the results from all differencing
339 epochs, so that only 3D surface change greater than ±0.103 m was considered in
340 the subsequent analysis. The horizontal (*xy*) and vertical (*z*) components of 3D
341 surface change were separated to aid the analysis and interpretation of moraine
342 surface evolution and were gridded to represent the mean of significant change
343 within regular 10 m^2 grid cells to account for variations in point density across the
344 site (Fig. 5, Fig. 6). Vertical surface change for a range of epochs, encompassing
345 intra-annual and annual change, are displayed in Fig. 5, whilst illustrative horizontal
346 components of 3D change for intra- and inter-annual differencing epochs are shown
347 in Fig. 6. The longest differencing epoch, representing a period of ~400 days (Fig.
348 5b) shows a broad pattern of net uplift across the moraine of the order of 0.074 m.
349 Locally, uplift exceeds 0.2 m across parts of the moraine complex, and, whilst on first
350 glance these elevation gains appear to be largely randomly distributed across the
351 site, on closer inspection they occur predominantly on or adjacent to the main,

352 central moraine ridge and close to the current ice margin. The large central moraine
353 ridge exhibits a mean uplift of 0.11 m, whilst specific ice-marginal areas to the west
354 and an area of moraine to the south-west of the embayment also exhibit uplift of a
355 similar magnitude (Fig. 5b). In contrast, an area in the southernmost sector of the
356 basin and an ice-marginal area to the centre-west exhibit a net reduction in moraine
357 surface elevation, up to a maximum of -0.354 m.
358
359 Intra-annual change detection mapping was undertaken using TLS-TLS and TLS-
360 SfM differencing (Fig. 5c, d). Key similarities between these two datasets, which
361 represent vertical topographic change over a ~31 and ~27 day period, respectively,
362 include uplift at the southern extent of the embayment (mean 0.081 m and 0.123 m
363 for the TLS-TLS and TLS-SfM differencing, respectively). Similarly, both datasets
364 reveal surface lowering at south-eastern, or true rear, of the basin (mean -0.106 m
365 and -0.112 m for TLS-SfM and TLS-TLS differencing, respectively), and, in the TLS-
366 SfM data, on the ice-distal (southern) side of the central moraine ridge (Fig. 5c; -
367 0.092 m). However, the large area of ice-marginal surface lowering (-0.095 - -0.373
368 m) that is detected in the TLS-SfM differencing results is not mirrored in the
369 equivalent TLS-TLS differencing data (Fig. 5d) and stems in large part from the
370 reduced spatial coverage of the usable TLS scan data acquired at the end of season
371 1, which comprised data from only two scan positions (Fig. 1c) and which omits the
372 ice-marginal zone.
373
374 The results of vertical change detection using both SfM-TLS and TLS-TLS
375 approaches also display similarities for differencing undertaken between the end of
376 season 1, and season 2 (Fig. 5e,f), including a largely continuous area of uplift
377 across the centre of the site, as well as areas of surface lowering along the eastern
378 edge of the site. Whilst widespread uplift characterises the entire western edge of
379 the study area in the TLS-TLS data (Fig. 5f), the equivalent SfM-TLS data instead
380 report the occurrence of surface lowering at the base of the hillslope spur which
381 forms the western boundary of the site (Fig. 5e). Furthermore, an area of
382 considerable (mean 0.218 m) uplift characterises the ice-marginal zone in the SfM-
383 TLS differencing data for this epoch, but, once again, the reduced spatial coverage
384 of the TLS datasets mean that no differencing data are available to verify or contest
385 this pattern. However, we note that vertical change at the ice-marginal (northern)
386 limit of the TLS-TLS data for both intra-annual and annual differencing epochs do not
387 correspond with the equivalent TLS-SfM or SfM-TLS results (Fig. 5c and 5e,
388 respectively) .
389

390   In light of our discussion of the sources of substantial topographic discrepancy
391   between the TLS and UAV-SfM datasets (Fig. 3; section 3.3), important questions
392   arise as to whether the differencing results in the ice-marginal zone, and in the
393   western sector of the site truly represent physical surface movement, both within
394   season 1, and between seasons (Fig. 5, 6). On balance, and despite the application
395   of a sufficiently large confidence threshold to remove non-significant change from the
396   differencing results (Table 2), we retain much less confidence in reported surface
397   displacement in these two zones than we do for the central portion and rear arc of
398   the moraine basin, where we note that the results of TLS-SfM and TLS-TLS
399   differencing for near-identical differencing periods exhibit a number of similarities.
400
401   **4.2. Lateral displacement**
402
403   Examples of horizontal displacement, calculated here as the xy component of the
404   orthogonal distance between two point clouds acquired at separate times, and
405   gridded to represent the average xy displacement within 10 m^2 grid cells, are shown
406   in Fig. 6 for intra- (Fig. 6a,b) and inter-annual epochs (Fig. 6c). A range of xy
407   displacement orientations are detected, and range from sub-centimetre to >0.2 m in
408   magnitude. Lateral displacements within season 1 are displayed for both TLS-TLS
409   and TLS-SfM differencing products (Fig. 6a and 6b, respectively).
410
411   A comparison of these two datasets reveal similarities, but also differences which
412   also likely arise from data quality issues in the north-west and ice-marginal sectors of
413   the site. Specifically, we cannot confidently corroborate the southerly displacement
414   vectors which are associated with substantial, yet questionable, ice-marginal surface
415   lowering in the TLS-SfM data (Fig. 6b). Similarly, the sparsity of TLS data coverage
416   in the western sector of the site makes validation of the northerly vectors associated
417   with surface uplift in the western sector of the site problematic. However, we note
418   that a similar pattern of vertical and lateral displacement is present in the inter-
419   annual TLS-TLS results in the western sector of the site (Fig. 6c), and so it remains
420   unclear as to whether this surface displacement is an artefact produced by poor data
421   quality. Elsewhere in the embayment, lateral displacements within season 1 exhibit
422   similarities between both sets of differencing data, including a dominantly westward
423   trajectory of surface movement, and a localised area of south- to south-westerly
424   movement at the extreme rear of the basin which is associated with a general
425   pattern of surface lowering in both datasets (Fig. 6a, 6b).
426
427   In contrast, total xy displacement over a >1 year period (Fig. 6c) appears to be less
428   uniform and comparatively chaotic. However, a number of local and largely

429 consistent patterns of horizontal displacement are discernible, such as
430 predominantly westward movement along the central moraine ridge, and north- to
431 north-eastern motion along the western edge of the site (Fig. 6c), which also occurs
432 within season 1 (Fig. 6a). Both trends are associated with net surface uplift. In
433 contrast, isolated patches of surface lowering are generally characterised by
434 southern or south-westerly *xy* displacement.

436 The analysis of surface profile transects shed further light on the evolution of surface
437 topography (Fig. 4). These data are particularly useful for examining the interplay
438 between vertical and lateral moraine surface displacement, which is alluded to in Fig.
439 6. For example, a combination of surface uplift and lateral displacement between the
440 start and end of season 1 is visible between 28-40 m in profile A (Fig. 4, inset 1).
441 Similarly, lateral (southern) translation of the moraine surface between 15-22 m in
442 profile C (Fig. 4, inset 2) is visible for the same differencing epoch.

444 **5. Implications for glaciological process analysis**

446 Here we highlight some implications arising from the measurement of these short-
447 term changes in surface morphology. Topographically, the Patriot Hills blue-ice
448 moraine confirms the morphological observations of the embayment, described by
449 Fogwill et al. (2012) as comprising sloping terraces and blocky, pitted boulder
450 moraine ridges. These ridges are thought to be fed from beneath by steeply dipping
451 debris bands coming from depth, driven by ice-flow compensating for katabatic wind
452 ablation of the glacier. Vieira et al. (2012) classify what we term blue-ice moraines as
453 'supraglacial moraine', and the debris bands in the blue ice outside of the basin as
454 blue-ice moraines. It is from clasts emerging from these bands that Fogwill et al.
455 (2012) have produced their model of blue-ice moraine formation in the basin. The
456 supraglacial moraines of Vieira et al. (2012) are described as slightly creeping
457 debris-mantled slopes – both Fogwill et al. (2012) and Vieira et al. (2012) consider
458 the features in the basin as active, but without measurements of observations of
459 rates, or the nature of change. Our differencing results confirm the hypothesis that
460 these features are active, and develops this idea further to demonstrate that moraine
461 slope evolution is active over annual to intra-annual timescales.

463 Hättestrand and Johansen (2005) discussed the evolution of blue-ice moraine
464 complexes in Dronning Maud Land, Antarctica, and hypothesised that, following ice-
465 marginal deposition of debris when the adjacent ice surface was higher, the
466 subsequent lowering of the exposed ice surface would produce a slope 'outwards'
467 from an embayment, followed by gradual movement of material towards the ice-

468   margin in a manner similar to that exhibited by active rock glaciers – features that
469   Vieira et al. (2012) interpret in the next basin along the Patriot Hills range. However,
470   whilst the former holds true as an explanation for the general gradient of the Patriot
471   Hills moraine complex (e.g. Fig. 4), our results suggest that the short-term evolution
472   of the moraines does not necessarily conform to the latter hypothesis of such as
473   simple process of consistent downslope movement, and in fact exhibits far more
474   dynamic complexity.
475

476   The moraine ridges both close to, and far from the ice margin emerge as axes of
477   activity and uplift (Fig. 5c), despite initial field observations suggesting that the ridges
478   most distant from the exposed ice surface were older and less active. However, we
479   exercise caution in the interpretation of surface displacements in the western, and
480   ice-marginal sectors of the site due to UAV-SfM data quality issues, and instead
481   confine our discussion of geomorphological activity to the remaining ~50% of the
482   basin area, where we retain confidence in the results of TLS-TLS and TLS-SfM
483   differencing.
484

485   Fogwill et al. (2012) suggest that once upcoming debris is at a sufficient thickness,
486   wind-driven ablation shuts off. Our observations suggest that if this is the case, these
487   ridges are not left stagnant at this point. The interplay between ice flow and surface
488   elevation lowering by wind, but reduced by thicker debris, may continue despite the
489   possible ages of the surface debris relative to ridges closer to the contemporary
490   blue-ice margin. This activity is not simply confined to '*inward*' or '*outward*'
491   movement of moraines within the embayment, but also involves a lateral component
492   (Fig. 6). Whilst we are unable to corroborate the substantial surface lowering
493   reported in the TLS-SfM differencing for the ice-marginal zone within season 1 (Fig.
494   5c) and between seasons (Fig. 5e), areas of seemingly persistent uplift are located
495   on the ice-distal face of the central moraine ridge, as well as along moraine ridges
496   toward the rear of the basin. These trends appear in both the TLS-SfM and TLS-TLS
497   differencing results (Fig. 5, Fig. 6).
498

499   Similarly, surface lowering appears to operate at the rear, or southern, extent of the
500   basin within season 1 (Fig. 5c,d) and between the beginning of season 1 and the
501   end of season 2 (Fig. 5b). However, it is characterised by surface uplift from the end
502   of season 1 to the end of season 2 (Fig. 5e,f). This surface lowering trend may be
503   the product of focussed katabatic wind-driven sub-debris ice ablation, coincident with
504   a break (reduction) in slope. There may therefore exist an interplay between moraine
505   uplift and sub-debris ice ablation, where the latter dominates over the longest
506   differencing period (Fig. 5b,c). Sedimentological characterisation of the moraine

507 basin by Westoby et al. (2015) revealed low median surface grain sizes toward the
508 rear of the basin, which may be indicative of a longer sediment exposure time for, or
509 preferential exposure to, *in situ* weathering relative to the remainder of the site,
510 leading to the comminution of surficial deposits and the enhancement of sub-debris
511 ice ablation, which promotes terrain relaxation (e.g. Krüger and Kjær, 2000;
512 Schomacker, 2008; Irvine-Fynn et al., 2011; Staines et al., 2015).
513
514 Lateral movement within the moraine ridges (Fig. 6) may reflect lateral extension or
515 'stretching' of the ridges as they encroach into the embayment. Such lateral
516 movement is corroborated from the orientation of crevasse-based grooves in the
517 moraine (Fig. 2c). The apparent inward encroachment of the Patriot Hills moraines
518 (Fig. 6) may be the product of the pressure exerted on the moraines by glacier ice
519 flow into the embayment in compensation for preferential ice ablation by katabatic
520 winds, which is consistent with blue-ice moraine formation theory (Fogwill et al.,
521 2012). Finally, the close match of inter-season surface elevation cross-profiles (Fig.
522 5) points to medium-term stability of the moraine system. This conclusion will be
523 investigated through the application of cosmogenic isotope evidence to assess
524 change since the Holocene.
525
526 More broadly, this study has demonstrated the potential for the combination of
527 different high-resolution surveying technologies and advanced 3D topographic
528 differencing methods for elucidating the short-term evolution of glaciated and ice-
529 marginal landscapes. Whilst this study has focussed on the surface evolution of
530 Antarctic blue-ice moraines, the application of 3D differencing methods to quantify
531 change between repeat, accurate topographic surveys has a wide range of potential
532 glaciological applications, which cryospheric researchers have already begun to
533 capitalise on (e.g. Piermattei et al., 2015, Gabbud et al., 2015; Kraaijenbrink et al.,
534 2016). A key contribution of this study to the wider Earth surface dynamics
535 community is the demonstration of truly 3D differencing methods to reveal not only
536 vertical surface change, but also the magnitude and direction of any lateral
537 component to surface movement. Such methods may have particular value for
538 quantifying the 3D surface evolution of, for example, rock glaciers, degrading ice-
539 cored moraines, or slope instabilities in permafrost regions, where information
540 regarding both vertical and lateral components of landscape development may be
541 both of scientific interest and practical application.
542
543 **6. Summary**
544

545 This research has employed a combination of TLS and UAV-based SfM-MVS
546 photogrammetry and 3D differencing methods to quantify the topographic evolution
547 of an Antarctic blue-ice moraine complex over annual and intra-annual timescales.
548 Segmentation of lateral and vertical surface displacements reveal site- and local-
549 scale patterns of geomorphometric moraine surface evolution beyond a threshold
550 level of detection (95% confidence), including largely persistent vertical uplift across
551 the moraine complex, both within a single season, and between seasons. This
552 persistent uplift is interspersed with areas (and periods) of surface downwasting
553 which is largely confined to the rear of the moraine basin for both differencing
554 epochs, and in ice-marginal regions within season 1, the latter of which we deem as
555 non-significant. Analysis of lateral displacement vectors, which are generally of a
556 much smaller magnitude than vertical displacements, provide further insights into
557 moraine surface evolution.

559 A number of methodological shortcomings are highlighted. Briefly, these relate to the
560 incomplete spatial coverage afforded by the use of TLS in a topographically complex
561 environment, and issues associated with obtaining suitable ground control for SfM-
562 MVS processing and potential implications for the accuracy of SfM-derived
563 topographic data products. This research represents the first successful application
564 of a combination of high-resolution surveying methods for quantifying the
565 topographic evolution of ice-marginal topography in this environment. Furthermore,
566 we have demonstrated that, whilst a number of operational considerations must be
567 taken into account at the data collection stage, these technologies are highly
568 appropriate for reconstructing moraine surface topography and for quantifying Earth
569 surface evolution in glaciated landscapes more generally.

571 **Author contribution**

573 S. A. Dunning, J. Woodward, A. Hein, K. Winter, S. M. Marrero and D. E. Sugden
574 collected field data. TLS and SfM data processing and differencing were undertaken
575 by M. J. Westoby. Data analysis was performed by M. J. Westoby, S. A. Dunning
576 and J. Woodward. Manuscript figures were produced by M. J. Westoby. All authors
577 contributed to the writing and revision of the manuscript.

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Figure captions

Figure 1. Blue-ice moraine embayment, Patriot Hills, Heritage Range, Antarctica. **(a)** Geographical context of Patriot Hills within the Heritage Range, southern Ellsworth Mountains.**(b)** The Patriot Hills massif. The location of the study embayment and area displayed in **(c)** is highlighted in red. **(c)**: Detailed study site overview map. Contours and underlying hillshade are derived from a UAV-SfM-derived DEM. TLS positions for the start of season 1 are shown in red, blue and yellow. The two scan positions re-occupied at the end of season 1 are shown in blue, whilst the three scan positions reoccupied in season 2 are shown in blue and red. Background to **(a)** © U.S. Geological Survey, **(b)** 2015 DigitalGlobe, both extracted from Google Earth.

Figure 2. Field photographs of the Patriot Hills blue-ice moraine study site. **(a)** Panoramic photograph of the moraine embayment – view north-east towards the ice margin from the rear of the embayment. Area shown in **(c)** and position and view direction of camera **(b)** shown for reference. **(b)** View to the north-west with moraine crest in foreground and subdued, ice-marginal moraine surface topography in middle-ground. **(c)** Close-up of moraine topography, highlighting ridges and furrows on moraine crests and in inter-moraine troughs.

Figure 3. Results of vertical (Z_{diff}; m) differencing of the UAV-SfM and TLS datasets acquired at the end of season 1, represented as the mean difference within 10 m^2 grid cells. 83% of the UAV-SfM data were found to be within ±0.1 m of the equivalent TLS data. Profiles A-C are displayed in Fig. 4.

Figure 4. Moraine surface elevation profiles, extracted from gridded (0.2 m^2) digital elevation models of TLS- and SfM-derived topographic datasets. Profile locations are shown in Figures 3 and 6. Profiles A and B bisect the main central moraine crest, whilst profile C is located on moraine deposits at the back of the embayment. Inset numbered boxes in profiles A and C show areas referred to in the text.

Figure 5. Vertical component of 3D topographic change (Z_{diff}) overlain on a UAV-SfM-derived hill-shaded DEM of the Patriot Hills blue-ice moraine complex. Topographic evolution was quantified using the Multiscale Model to Model Cloud Comparison (M3C2) algorithm in CloudCompare software. Vertical change is represented as the mean of significant change beyond a threshold of ±0.103 m within 10 m^2 grid cells. **(a)** UAV-SfM orthophotograph of the study site. Panels **(b)** to **(f)** cover specific differencing epochs using a combination of TLS and SfM data (see panel headings). Dashed line in **(b)** to **(f)** indicates locations of primary moraine ridge crest.

Figure 6. Change detection mapping for **(a,b)** intra-annual (season 1 start to season 1 end) and **(c)** annual (season 1 start to season 2) differencing epochs. Horizontal difference vectors (XY_{diff}) are scaled by magnitude and oriented according to the

938   direction of change. The vertical component of 3D change (Z_{diff}) is shown in the
939   background. Transects A-C denote the location of moraine surface profiles displayed
940   in Fig. 3 and Fig. 4. Red dashes on all panels shows the approximate location of
941   primary moraine ridge crest.
942
943   **Table 1.** Terrestrial laser scanning and UAV-SfM survey dates and registration
944   errors. Within each season, individual scans were registered to a single static
945   position to produce a single, merged point cloud (scan-scan registration error). TLS
946   data from the end of season 1 and for season 2 were subsequently registered to TLS
947   data acquired at the start of season 1, producing a project-project registration error.
948   The UAV-SfM data (season 1 end) were registered to TLS data from the end of
949   season 1.
950
951   **Table 2.** Registration error propagation for specific differencing epochs. The
952   propagated error for each differencing epoch is calculated using Eq. 3. The 95%
953   level of detection, or detection threshold is calculated in M3C2 as the product of the
954   propagated error and a measure of local point cloud roughness (Lague et al., 2013).
955   The results of 3D differencing were filtered in CloudCompare so that only differences
956   largest than the most conservative (largest) $LoD_{95\%}$ (i.e. 0.103 m) were considered to
957   represent significant change.

Table 1

Field survey	Scan position	Scan date	Scan-scan registration error (RMS; m)	Project-project registration error (RMS; m)
Season 1 start (TLS)	1	07 Dec 2012	Static	Static
	2	08 Dec 2012	0.0327	
	3	08 Dec 2012	0.0391	
	5	09 Dec 2012	0.0301	
	6	01 Dec 2012	0.0258	
	7	11 Dec 2012	0.0258	
Season 1 end (TLS)	1	09 Jan 2013	Static	0.0145
	2	09 Jan 2013	0.0145	
Season 1 end (UAV-SfM)	-	05 Jan 2013	-	0.0306
Season 2 (TLS)	1	14 Jan 2014	Static	0.0149
	2	14 Jan 2014	0.0205	
	3	14 Jan 2014	0.0255	

959 **Table 2**

960

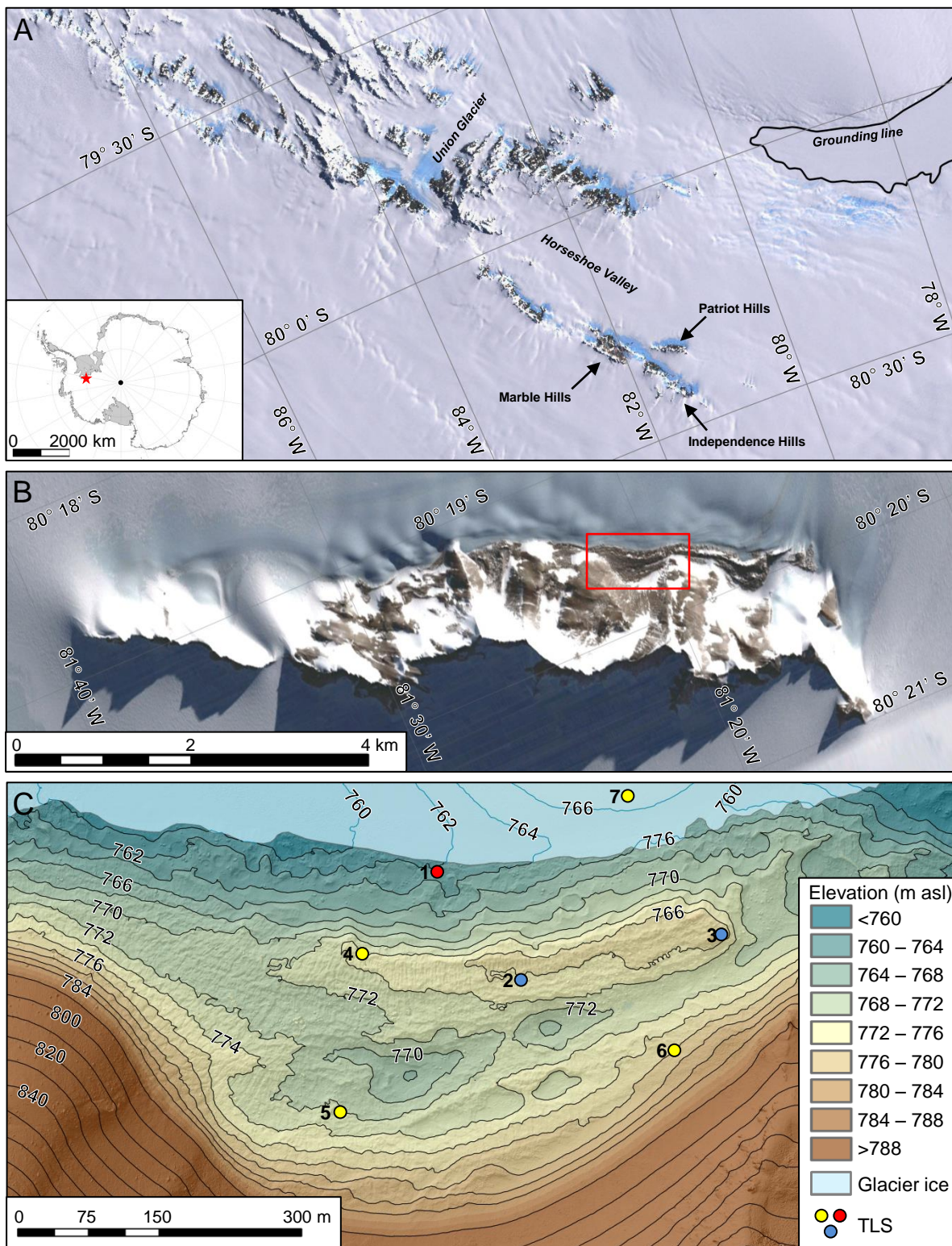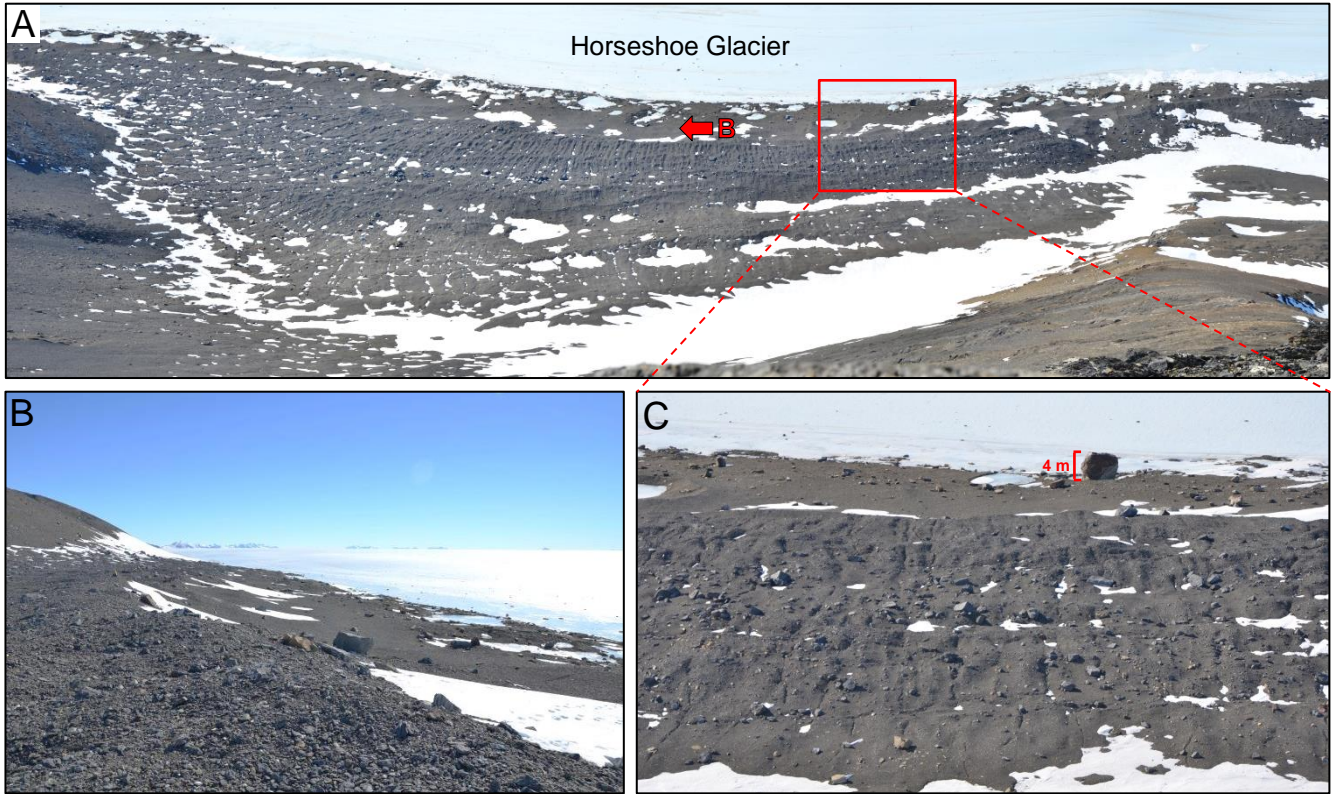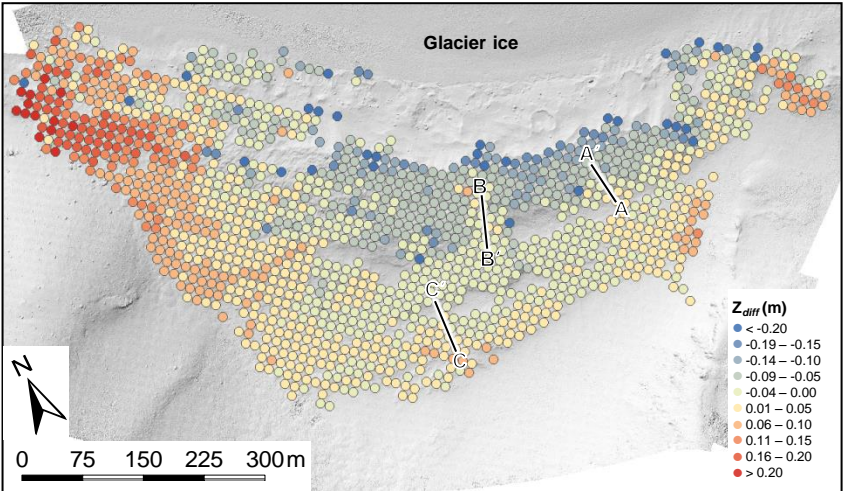| Differencing epoch	Propagated error (RMS; m)	M3C2 $LoD_{95\%}$ (m)
S1 start (TLS) - S1 end (TLS)	0.049	0.098
S1 start (TLS) - S1 end (SfM)	0.050	0.103
S1 end (TLS) - S2 end (TLS)	0.048	0.098
S1 end (SfM) - S2 end (TLS)	0.049	0.102
S1 start (TLS) - S2 end (TLS)	0.050	0.099

Figure 1

Figure 2

Horseshoe Glacier

Figure 3

Figure 4

Figure 5

A: UAV-SfM orthophoto

Glacier ice

0   75   150   225   300 m

Z_{diff} (m)
- < -0.20
- -0.19 – -0.15
- -0.14 – -0.10
- -0.09 – -0.05
- -0.04 – 0.00
- 0.01 – 0.05
- 0.06 – 0.10
- 0.11 – 0.15
- 0.16 – 0.20
- > 0.20

B: Season 1 start to season 2 end (TLS-TLS)

C: Season 1 start to season 1 end (TLS-SfM)

D: Season 1 start to season 1 end (TLS-TLS)

E: Season 1 end to season 2 end (SfM-TLS)

F: Season 1 end to season 2 end (TLS-TLS)

Figure 6

A: S1 start (TLS) to S1 end (TLS)

Glacier ice

XY$_{diff}$ (m)
< 0.01
0.01 – 0.02
0.02 – 0.03
0.03 – 0.04
0.04 – 0.05
0.05 – 0.10
0.10 – 0.20
> 0.20

Z$_{diff}$ (m)
< -0.20
-0.19 – -0.15
-0.14 – -0.10
-0.09 – -0.05
-0.04 – 0.00
0.01 – 0.05
0.06 – 0.10
0.11 – 0.15
0.16 – 0.20
> 0.20

0   75   150   225   300 m

B: S1 start (TLS) to S1 end (UAV-SfM)

C: S1 start (TLS) to S2 end (TLS)