The Cryosphere Discuss., 7, C1785–C1802, 2013
www.the-cryosphere-discuss.net/7/C1785/2013/

The Cryosphere Discussions
Open Access

Interactive comment on "Low-cost, on-demand aerial photogrammetry for glaciological measurement" *by* K. Whitehead et al.

K. Whitehead et al.

kwhitehe@ucalgary.ca

Received and published: 17 September 2013

Reviewer 1

Reviewer 1 comment 1

This article details the acquisition and analysis of two DEMs acquired by unmanned aerial vehicle (UAV) and by photography from helicopter. With the article focus on "low-cost", perhaps the authors could comment on their actual cost and the relative cost versus alternatives given their study area is not cheaply accessible by plane and helicopter.

The following was added to end of the introduction section: It is recognised that helicopter time is expensive, with typical rates being in the region of $2,000 per hour. How-

ever many glaciological studies require the use of helicopters for access purposes. The survey described in this study took less than 15 minutes of additional helicopter time to execute, making it considerably less expensive than custom aerial photo or satellite image acquisitions.

Reviewer 1 comment 2

Line 4: “Until recently it was believed that this glacier had changed little in recent years.” : : : this is much too vague – please give a date, and back up with a reference

This has now been changed to: According to Moorman (2003) the glacier terminus first started to show signs of retreat in 1996. Wainstein et al. (2008) also showed that the terminus region thinned by approximately 25 meters between 1982 and 2007. A new reference was added: Moorman, B. Glacier-permafrost hydrology interactions, Bylot Island, Canada. Proceedings 8th International Permafrost Conference, Zurich, Switzerland, Phillips, M., Springman, S.M., Arenson, L. (eds), pp:783-788, A.A. Balkema Publishers, 2003.

Reviewer 1 comment 3

Line 5: “However, Wainstein et al. (2008) showed that the terminus region has thinned by approximately one meter per year since 1982.” After the previous sentence this implies that other researchers on this glacier had failed to observe any change. However previous research has indicated no change 1982-96 but retreat since then. Hence the ‘one meter per year’ must be a coarse average with 0m/yr 1982-96 and 2m/yr 1996-2008 ?

This comment is addressed in the answer to comment 2 above.

Reviewer 1 comment 4

P3046, line 15-16: these two sentences can be joined, i.e. : : :camera, with a retractable lens

TCD
7, C1785–C1802, 2013

This has now been changed as suggested.

Reviewer 1 comment 5

P3047, line 9: Impho software – provide more info, who is the supplier ?

The following line has been added: Which is a full-featured digital photogrammetry package produced by Trimble.

Reviewer 1 comment 6

Line 20: no need to mention Impho again : : :

Removed reference to Inpho and merged both sentences.

Reviewer 1 comment 7

3048, line 12: using a nominal -> with a nominal

This has now been changed as suggested.

Reviewer 1 comment 8

There are a number of issues of clarity and explanation in this section Line 11-12: 'Although the differences appear small at the scale shown' : : : the differences (>2-2.5m for one year) are surely sizeable, and how is 'the scale shown' relevant - would the differences somehow appear greater at a larger scale ? : : :

This line has been replaced by: Figure 3a shows a comparison of the glacier terminus position in 2010 and 2011. In general, changes were too small to be measurable. However region A on the northern side of the terminus showed significant loss of ice, which was most likely caused by undercutting from the adjacent marginal stream. The change at B is believed to be due to the loss of a major block of ice from the northern calving face. The changes shown at C reflect erosion caused by the main supraglacial stream as it flowed onto the proglacial floodplain.

Reviewer 1 comment 9

TCD
7, C1785–C1802, 2013

Line 12: signiïňĄcant loss of ice occurred in regions A and B : : :. Why are A, B and C the only 'signiïňĄcant' occurrences of loss – they are not even visible as higher loss on ïňĄg 3b. and what does 'signiïňĄcant' mean in this context ? .. what prevents the areas of highest loss (e.g. > 2.0m) from being worthy of 'signiïňĄcance' ? The word signiïňĄcant is thus overused in both lines 17 and 18 : : : (choose an alternative)

This comment has been dealt with in the answer to comment 8.

Reviewer 1 comment 10

Line 22; where are the moraine regions that are referred to – I don't see them in ïňĄg 3b (with regards to 'small amounts of thickening')

This section now reads: In general, the differences in surface elevation were between 1.5 m and 2.5 m on the northern side of the glacier, with differences of between 1.0 m and 1.5 m closer to the centre. Ice-free areas adjacent to the glacier generally showed little change. However thickening in excess of 1 m can be seen for the proglacial icing, which is located to the east of the terminus.

Reviewer 1 comment 11

Line 24-25: large amounts of thickening reflect actual changes to the proglacial icing; these are hardly distinguishable due to the clipping of the DEM close to the edge of the glacier – are there more DEM data beyond the glacier to make this point clearer ?

Figure 3b has been amended to include as much of the area around the glacier as possible. The colour scheme has also been changed.

Reviewer 1 comment 12

Figure 3c gives a clear image of rate of ice ïňĆow, but the reader has no context relative to other arctic glaciers. Can any articles be cited to give ïňĆow rates from other comparable studies ?

The following sentence has been added to this section: Displacements derived from

TCD
7, C1785–C1802, 2013

manual feature tracking were compared with displacements for the same area obtained from SAR interferometry [10], and were generally found to agree to within 0.5 ma-1.

Reviewer 1 comment 13

Line 12-13. Remove the duplicative sentence: “In each case : : : check points”

This has now been changed as suggested.

Reviewer 1 comment 14

lines 28-30 and 36-38: The articles by Wainstein et al, and Whitehead et al (2010) are inadequately referenced without page numbers; 2010 appears three times in each citation, including the cryptic ‘GEO2010 Calgary Organizing Committee’.

These references have now been amended as requested.

Reviewer 2

Reviewer 2 comment 1

References to the term low cost need to be clariïňĄed. Cameras and the UAV and its navigation sensors can be considered of low cost. The camera used with the helicopter is of low cost. But the use of the helicopter and the INPHO photogrammetric software do not fall under the low cost umbrella.

The cost of helicopter time has been addressed in the answer to reviewer 1 comment 1. The cost of Inpho is addressed in the answer to comment 5 below.

Reviewer 2 comment 2

Pa 2; Lines 10-17. Helicopters should be included in the list of data acquisition platforms. The issue of georeferencing of the remotely sensed data should be addressed also in the glaciological studies.

This section now reads: Typically, remote sensing data used in glaciology are acquired from fixed-wing aircraft, helicopters, or satellites, with researchers often having to rely

TCD
7, C1785–C1802, 2013

on imagery gathered for other purposes, such as government map updates (e.g. Wainstein et al. 2008). Satellite imagery may be appropriate for some types of measurements, but it may be subject to limitations such as cost, weather conditions, and resolution. Georeferencing may also pose significant challenges in some glaciated areas, where stable reference points are unavailable.

Reviewer 2 comment 3

Pa 2; line18.: : :..from OVERLAPPING images

This has now been changed as suggested.

Reviewer 2 comment 4

Pa 2; line 19.: : :: : : SPATIO-TEMPORAL changes

This has now been changed as suggested.

Reviewer 2 comment 5

Pa 2; line 20. List examples of publically available software with references

This section has been changed to read: The Inpho package used in this study is designed for high-throughput aerial surveys. As such it does not fall into the category of budget software. However much of the functionality of this software can be duplicated by freely-available packages such as SFMToolkit3 and Bundler (e.g. Westoby et al. 2012), and Microsoft's Photosynth (e.g. Fonstad et al. 2013), complemented by point cloud editing software such as Meshlab (e.g. Fonstad et al. 2013).

Reviewer 2 comment 6

Pa 2 and 3; line 21-23 and 1-2. The statement is not absolutely correct. Analytical photogrammetric software packages since the 80's handle large rotation angles. So this is not a recent functionality.

This sentence has now been deleted.

TCD
7, C1785–C1802, 2013

Reviewer 2 comment 7

Pa 3; line 6. Based on the large forward and sidelap overlaps, stereo could be replaced by multiview overlapping imagery.

Replaced the term stereo imagery by “multiple stereo image combinations”

Reviewer 2 comment 8

Pa 3; line 7. Please indicate onboard navigation sensors including their positioning and angular accuracies.

This paragraph has now been replaced. The new paragraph reads as follows: A parallel development is the advent of lightweight, low-cost unmanned aerial vehicles (UAVs). These resemble radio controlled hobby aircraft, but fly autonomously according to a pre-programmed flight path. Flight planning software establishes the optimal image coverage, so that the area of interest is fully covered by multiple stereo image combinations. The aircraft then flies the predetermined course, using an onboard autopilot to guide the flight and image acquisition. Typically the autopilot receives inputs from an integrated Global Navigation Satellite System (GNSS) and Inertial Measurement Unit (IMU), which will provide X, Y, and Z positions to within 10 m, and values for aircraft roll, pitch, and yaw to better than 2°. On completion of the flight, a log file is normally downloaded from the aircraft. This file gives provisional X, Y, and Z positions, as well as values for aircraft roll, pitch, and yaw, which are logged several times a second. This information can be used as an input to a photogrammetric block-adjustment process.

Reviewer 2 comment 9

Pa 3; line8-9. Besides orientation (angular) parameters most probably position parameters are provided as well in the log ïňĄle. Please clarify the log parameters.

This comment has been dealt with in the response to comment 8 above.

Reviewer 2 comment 10

TCD
7, C1785–C1802, 2013

Pa 3; line13. Figure 1c Pa 3; line17. Should be digital elevation and orthomosaic image and the digital elevation is a prerequisite for the creation of orthoimages.

Line 17 now reads: Through processing we generated a Digital Elevation Model (DEM) and an orthomosaic.

Reviewer 2 comment 11

Pa 4; Line 11. (Figure 1c) Pa 4; line 17. How was f=5.1mm was determined. Was any camera calibration performed?

This line has now been revised to read: To keep camera lens parameters consistent with the values established for the existing camera calibration, the zoom was set to the widest possible coverage, giving an effective focal length of approximately 5.1 mm.

Reviewer 2 comment 12

Pa 4; line 19. The FORWARD overlap

This has now been changed as suggested.

Reviewer 2 comment 13

Pa 5; line 4. Please indicate type of GPS receiver used to determine the coordinates of the control/check points.

This description has now been changed to: Using a Trimble dual-frequency GPS receiver operating in Real Time kinematic (RTK) mode.

Reviewer 2 comment 14

Pa 5; 3 and 15. Please provide a diagram of the location of the GCP and CHK points

Figure 2a has been amended to show the location of all GCPs and check points used.

Reviewer 2 comment 15

Pa 5; line 8, 10, 11, 17. Please clarify the use of the terms Aerial triangulation and

TCD
7, C1785–C1802, 2013

block adjustment. Block adjustment is a method of performing aerial triangulation. As INPHO software has been used most probably we are talking about automated image matching for locating tie point among images followed by a bundle photogrammetric block adjustment (block refers to simultaneously adjust the entire block of images).

This section now reads: Aerial Triangulation (AT) was carried out using the Match-AT module of Inpho, which is a full-featured digital photogrammetry package produced by Trimble. This process uses conjugate points identified across multiple overlapping images in order to carry out a bundle-block adjustment, allowing photo centre positions and camera rotations to be reconstructed from a small number of GCPs.

The first line of the following paragraph has been amended to read: Following the AT process, a 1 m resolution DEM was generated for the entire survey area using the Match-T DSM module of Inpho.

Reviewer 2 comment 16

Pa 5; line 12. Is the calibration reïňĄnement referred to camera calibration using the camera self-calibration additional parameter. Please clarify. Also clarify if it was photo-variant or photo-invariant approach.

This section has now been changed to read: The AT process was carried out three times. The first time, all the GCPs were used to give the best overall adjustment. Match-AT was then rerun with the self-calibration option selected in order to minimize residuals. This process does not make changes to the camera focal length, but rather generates a correction grid for the camera which optimally models lens distortion across the entire block of photos.

Reviewer 2 comment 17

Pa 5; line 8. Please give reference for the INPHO

This was addressed in response to comment 5 from reviewer 1.

TCD

7, C1785–C1802, 2013

Reviewer 2 comment 18

Pa 5, line 17-19. It is not clear if the DEM (DSM) generated automatically? If yes how was the point matching performance considering the low texture of the images.

The section on DEM creation has been amended and now reads: Following the AT process, a 1 m resolution DEM was generated for the entire survey area using the Match-T DSM module of Inpho. This package used an automated point matching technique to generate a dense surface model of the survey area. Because the ice surface was generally snow free, the images were strongly textured, providing optimal conditions for point matching and DEM creation.

Reviewer 2 comment 19

Pa 5; line 18. How/what system was used for the manual 3D measurements?

This section now reads: Direct measurements of the glacier surface elevation were made in 3D from the source imagery, using Inpho's DT Master editing suite. These elevations were typically within 0.5 m of the DEM elevation. However elevation discrepancies of several metres were noted in steeply-sloping marginal areas, and in the vicinity of the main supraglacial stream.

Reviewer 2 comment 20

Pa 5; line20. Please give an indication of the magnitude of the elevation discrepancies.

See answer to comment 19 above.

Reviewer 2 comment 21

Pa 5; line 22. Please provide a ïňĄgure showing the digital surface elevation (raster format)

Because of the elevation range across the surface we believe that a raster image would not provide any useful additional information, and would require the figure limit to be

TCD
7, C1785–C1802, 2013

exceeded. Figures 2a and 2b are shown with 10 m contours in order to represent the DEMs generated in each year and to show the similarity between them.

Reviewer 2 comment 22

Pa 6; line 7. Please note camera ïňĄeld of view time 1: 96deg; time 2:75deg. Please provide examples of the images captured, one from time 1 and one from time 2 covering approximately the same area.

We calculate angular values of 76.7° and 63.4° respectively for camera FOV. However we recognise that with different definitions of sensor size and angular coverage this statement may cause confusion. The sentence has been changed to omit any reference to camera field of view and now reads: This camera had a sensor size of 17.3 mm by 13 mm, with an image size of 4000 by 3000 pixels, and was used with a fixed 14 mm lens. We believe that providing sample images from each camera at a useful scale would increase the size of the article significantly, while adding little extra value to its content.

Reviewer 2 comment 23

Pa 6; line12. What values were used for the angular elements of the camera?

The following sentence was added: The camera was assumed to be pointing straight down and oriented parallel to the flight lines.

Reviewer 2 comment 24

Pa 6; line 15. Again please provide diagram with the location of GCP and CHK points

Figure 2b has been amended to show the location of all GCPs and check points used.

Reviewer 2 comment 25

Pa 6; line23. Same as in Pa 5; line 8, 10, 11, 17.

This line has been amended to remove any confusion between the terms aerial trian-

TCD
7, C1785–C1802, 2013

gulation and block adjustment. It now reads: Nine well-distributed GCPs were used as independent check points to estimate overall accuracy, with the remaining points used for the AT process.

Reviewer 2 comment 26

Pa 7; line 14 and Figure 3a. Please use appropriate scale to illustrate spatial differences for a couple of areas (zoom-in)

This figure has now been amended to show a detailed view of the changes occurring around the supraglacial stream (area C). The caption now reads: Figure 3, a) Changes in glacier margins from 2010 to 2011 (inset shows detail of changes around the exit point of the supraglacial stream). No other insets have been added for area A or B due to the limitations of space.

Reviewer 2 comment 27

Pa 8; line 2-3. Was any independent validation performed on the ice ïňĆow speed (0 m/yr and 8 m/yr)?

This was addressed in response to reviewer 1, comment 12.

Reviewer 2 comment 28

Pa 8; line 17. Please provide indicative accuracy results of the bundle block triangulation, such as RMS values of the image coordinates, of the GCPS and of the CHK points.

This section has been amended to read: For 2010, the RMS error of the image coordinates was 2.3 μm in both x and y, the GCPs used in the block adjustment process had RMS errors of 0.04 m in both X and Y, and 0.04 m in Z, whereas the check points used had RMS errors of 0.18 m, 0.21 m, and 0.42 m in X, Y, and Z, respectively. For 2011, the RMS error of the image coordinates was 2.4 μm in x and 2.6 μm in y, the GCPs used in the block adjustment process had RMS errors of 0.01 m in both X and Y, and

TCD
7, C1785–C1802, 2013

0.004 m in Z, with RMS errors for the check points of 0.63 m, 0.52 m, and 0.19 m in X, Y, and Z.

Reviewer 2 comment 29

Pa 10; line 7. Equivalency of photogrammetric and lidar data can be achieved under certain conditions. We also need to separate between planimetric and height equivalencies. For example while there is mentioning of vertical lidar accuracies of 0.2m there is no mentioning of the planimetric accuracies in this case.

The following sentence has been added to this section: Planimetric accuracies reported in the current study are also similar to those reported by Arnold et al. (2006), and Hopkinson et al. (2009), who both estimated XY accuracies as being between 0.3 m and 0.4 m.

Reviewer 2 comment 30

Pa 12; line 17 and Pa 13; line 1. Are the proceedings of the GEO2010 available?

These references have now been amended – see reviewer 1 comment 14.

Reviewer 2 comment 31

Pa 11: References are mainly from the geoscience ïňĄeld. Much and very important work have been done in the ïňĄeld of photogrammetry (e.g., publications by the International Society for Photogrammetry and Remote Sensing (ISPRPS)).

It is certainly true that our background references are focussed towards geosciences. However the focus of this paper is on practical techniques which are likely to be of use to glaciologists. As such we have focussed more on demonstrated applications, using existing available software, rather than recent developments in photogrammetry. Given the length of this article we feel that the references cited provide the most informative context for the article as presented.

Short comment

TCD
7, C1785–C1802, 2013

The purpose of Figure 1c should be to show the vehicle and provide a sense of scale for the vehicle. The person in the photograph does provide a nice sense of scale, but the vehicle itself only occupies 10% of the image. I recommend a new photo that maximizes the viewing of the vehicle itself. A ruler could be included to provide a sense of scale. You could possibly include an inset that focuses on the main body of the vehicle. I am interested in seeing the propeller system and where the camera is mounted, but I can barely see the vehicle in the present image.

An additional figure (1d) has been added to provide additional detail of the camera pod and propeller assembly. The caption for this figure now reads: Figure 1, a) Location of site on Bylot Island, b) Landsat 7 image of Fountain Glacier, c) Carrying out pre-flight checks for the Outlander UAV, d) Close up of propeller assembly showing the location of the camera pod.

Editors comments

Editors comment 1

The readers might be interested to obtain a rough cost estimate. Acquiring imagers with UAV's probably low cost once the UAV is purchased. However, a helicopter flight can be quite expensive.

This was addressed in response to reviewer 1 comment 1.

Editors comment 2

Please provide some more information about the co-registration of the DEMs.

The following sentence was added to the end of Section 3.2 Accuracy Estimates: These figures also suggest that registration errors between the two 1 m resolution DEMs are unlikely to exceed one pixel on the glacier surface.

Editors comment 3

The accuracy on the result seems to be quite high and the technique is therefore suit-

TCD
7, C1785–C1802, 2013

able for smaller areas. However, much more effort is required if larger parts of the glaciers should be covered. Please shortly mention and discuss this.

The following has been added to paragraph 1 of the Discussion and Conclusions: Limitations imposed by battery life, and the challenges of operating beyond line of sight, do however currently impose limitations on the size of areas which can be covered by UAV surveys. For example, a survey of the entire 16 km length of Fountain Glacier would require multiple flights and would necessitate physical access to the upper glacier, both for control survey and for the purposes of take off and landing.

Interactive comment on The Cryosphere Discuss., 7, 3043, 2013.

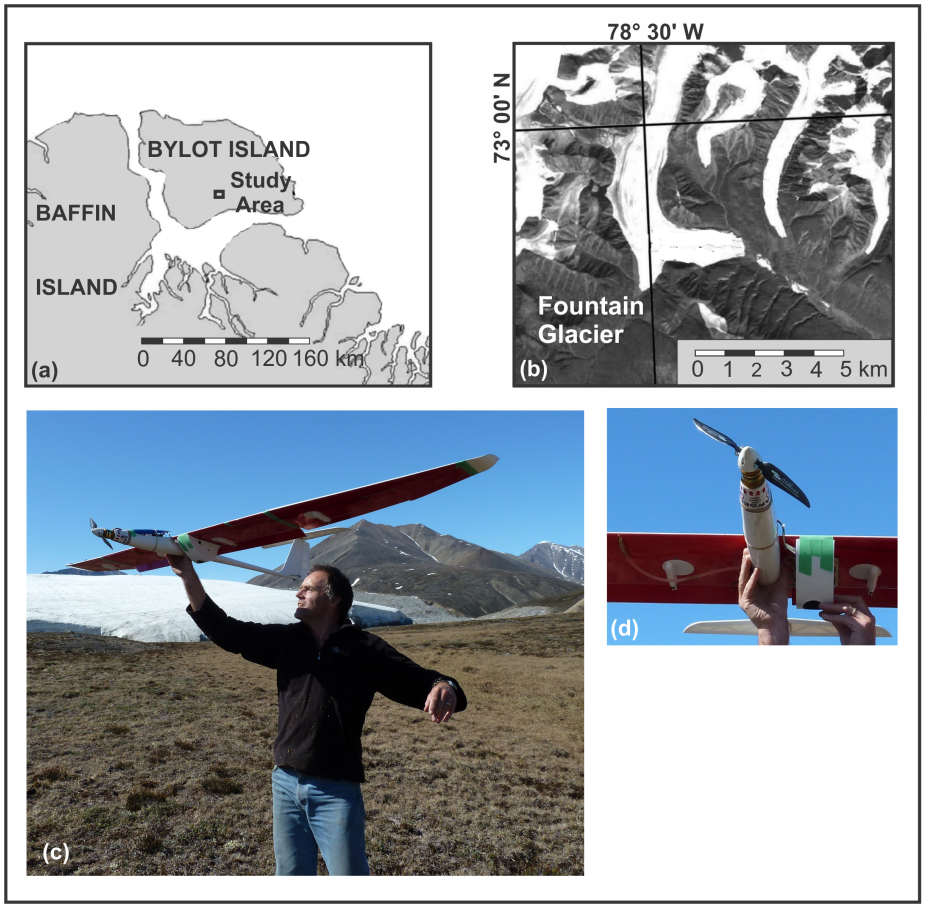

Fig. 1.

TCD
7, C1785–C1802, 2013

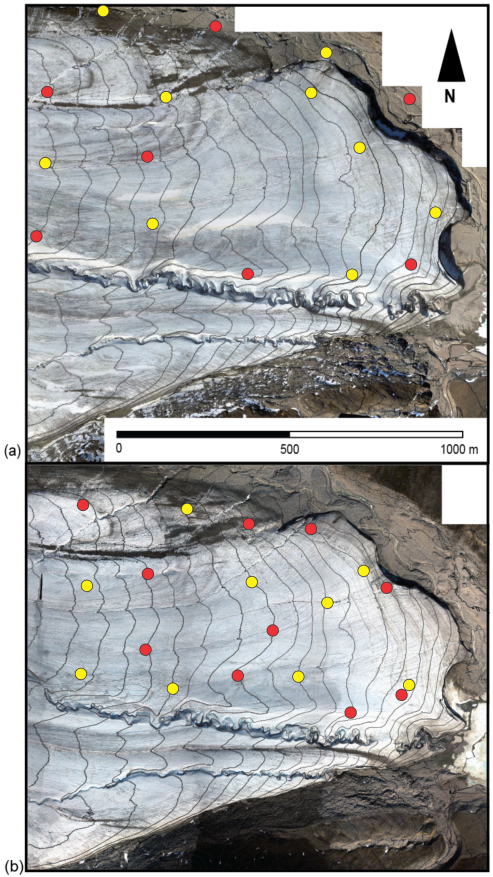

Fig. 2.

TCD
7, C1785–C1802, 2013

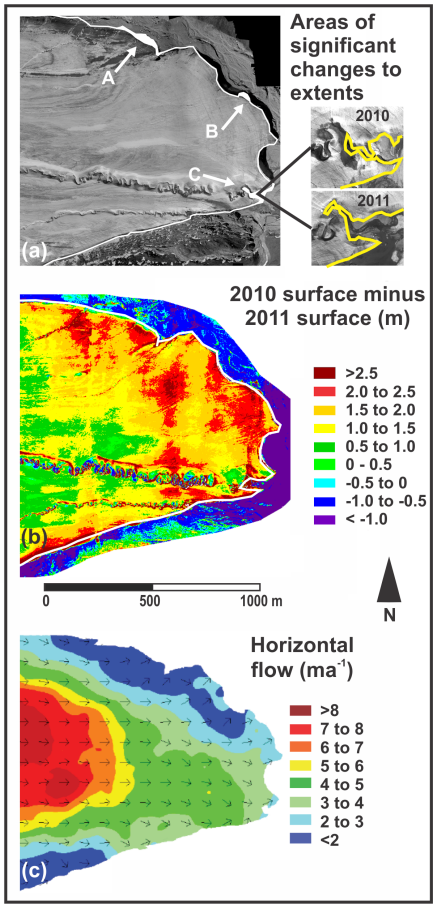

Fig. 3.

TCD
7, C1785–C1802, 2013