1   **Significant submarine ice loss from the Getz Ice Shelf, Antarctica**

2   *David M. Rippin*

3   *Department of Environment and Geography, University of York Wentworth Way, Heslington, York,*
4   *YO10 5NG.*

5   **1. Abstract**

6   We present the first direct measurements of changes taking place at the base of the Getz Ice Shelf
7   (GzIS) in West Antarctica. Our analysis is based on repeated airborne radio-echo sounding (RES)
8   survey lines gathered in 2010 and 2014. We reveal that while there is significant variability in ice
9   shelf behaviour, the vast majority of the ice shelf (where data is available) is undergoing basal
10   thinning at a mean rate of nearly 13 m a^{-1}, which is several times greater than recent modelling
11   estimates. In regions of faster flowing ice close to where ice streams and outlet glaciers join the ice
12   shelf, significantly greater rates of mass loss occurred. Since thinning is more pronounced close to
13   faster-flowing ice, we propose that dynamic thinning processes may also contribute to mass loss
14   here. Intricate sub-ice circulation patterns exist beneath the GzIS because of its complex sub-ice
15   topography and the fact that it is fed by numerous ice streams and outlet glaciers. It is this
16   complexity which we suggest is also responsible for the spatially variable patterns of ice-shelf change
17   that we observe. The large changes observed here are also important when considering the
18   likelihood and timing of any potential future collapse of the ice shelf, and the impact this would have
19   on the flow rates of feeder ice streams and glaciers, that transmit ice from inland Antarctica to the
20   coast. We propose that as the ice shelf continues to thin in response to warming ocean waters and
21   climate, the response of the ice shelf will be spatially diverse. Given that these measurements
22   represent changes that are significantly greater than modelling outputs, it is also clear that we still
23   do not fully understand how ice shelves respond to warming ocean waters. As a result, ongoing
24   direct measurements of ice shelf change are vital for understanding the future response of ice
25   shelves under a warming climate.

26

27   **2. Introduction**

28   Warming ocean waters are a recognised consequence of global warming trends, and ice shelves
29   which float in these warming waters are prone to significant melting activity. This is important
30   because ice shelves are an interface between grounded ice and the oceans and are therefore sites
31   where these key interactions occur (Berger *et al*., 2017). For example, past work has shown that
32   many of the ice shelves found along the Antarctic Peninsula have, in recent years, undergone
33   significant and rapid retreat, and in some cases collapse (e.g. Rott et al., 1998; Holt et al., 2013).
34   There is evidence of a gradual southwards progression of these occurrences, suggesting that there is
35   an underlying climatic cause (Schannwell, 2018). Such changes are significant because ice shelves
36   have a crucial role to play in regulating the rate of grounded ice-loss to the oceans (e.g. Scambos et
37   al., 2000, 2004; Dupont and Alley, 2005; Pritchard et al., 2012; De Rydt et al., 2015). Although the
38   mechanisms behind these changes are complex, any thinning enhanced by basal melting is caused
39   by variations in oceanic temperature and ocean circulation due to oceanic warming (e.g. Pritchard et
40   al., 2012).

41 Of the order of 74% of Antarctica is bounded by these floating ice shelves (BIndschadler *et al*., 2011;
42 Berger *et al*., 2017), and the Getz Ice Shelf (GzIS) is one of many regions of floating ice around the
43 Antarctic Peninsula. It is approximately 650 km in length and covers an area of approximately 33,395
44 km^2, occupying a portion of the Antarctic perimeter in the Amundsen Sea (Jacobs et al., 2013; Rignot
45 et al., 2013). A recent modelling study also showed that of all the Antarctic ice shelves, it is those of
46 the Amundsen Sea (including the GzIS) where greatest changes are forecast to happen in the
47 decades to come, as a result of warming ocean waters (Naughten *et al*., 2018). Understanding the
48 changes going on here are thus of great importance, and arguably greater importance than
49 elsewhere. Amongst Antarctic ice shelves, the GzIS is unique because its large size and position
50 means that it is exposed to a more varied ocean environment than other ice shelves (Jacobs et al.,
51 2013). It also differs from other ice shelves because it is fed by numerous glaciers and ice-streams.
52 Furthermore, it is characterised by a margin which is anchored by many small islands and inland
53 grounded regions, and it is thought that these might have an impact on calving rates and on
54 circulation of ocean waters in sub-ice cavities (e.g. Rignot et al., 2011; Jacobs et al., 2013). Previous
55 work has suggested that Circumpolar Deep Water (CDW) beneath the GzIS may actually be cooler
56 than that found elsewhere (Jacobs and Giulivi, 2010; Jacobs et al., 2012; Jacobs et al., 2013), and
57 combined with the sheer size of the GzIS and its complex ocean-boundary, there may be highly
58 variable rates of submarine melting here. Despite these suggestions, in reality, relatively little is
59 known about general rates of submarine melting beneath floating ice-shelves (Horne et al., 1985;
60 Walters et al., 1988; Motyka et al., 2003), let alone the nature of such complexity which may exist
61 here in the GzIS. Wilson and Straneo (2015) do suggest that where ice tongues are thickest, and
62 where ocean waters are warmer and deeper, submarine melt rates are at their greatest (cf. Seroussi
63 et al., 2011), however, significant complexity around this basic rule is expected. Despite
64 uncertainties, the importance of understanding the magnitude of ice shelf loss, as well as any spatial
65 complexity and variability is significant, because of the potential for ice shelves to collapse with
66 consequent implications for the flow of grounded ice to the oceans, and on overall ice-sheet stability
67 (Dupont and Alley, 2005; 2006; Kulessa et al., 2014). The GzIS is of particular importance because
68 not only is it particularly vulnerable to warming ocean waters, but future predictions suggest
69 warming-induced losses will be most pronounced of all the Antarctic ice shelves, and because of its
70 complexity, there is likely to be considerable spatial variation in the response of the ice shelf to this
71 oceanic warming.

72 In 2013, Jacobs et al. collected profiles at sub-ice cavity openings along the GzIS to measure water
73 temperature, salinity and dissolved oxygen content. From satellite-derived measurements of ice flux,
74 modelling and other observations they calculated that through the 2000s, there was marked
75 variability in ice shelf mass balance, with a positive mass balance in 2000 but a negative mass
76 balance in 2007. These observations are invaluable but do not represent absolute and direct
77 measurements of sub-ice melting and to date there have been no direct measurements of such
78 losses on the GzIS. There has, however, recently been an attempt to explore subglacial melting
79 directly on Antarctic ice shelves elsewhere (Khazendar et al., 2016). Khazendar et al. (2016) directly
80 quantified submarine melting of the Dotson and Crosson ice shelves in the Amundsen Sea Sector of
81 West Antarctica from observation of repeat Operation IceBridge radio echo-sounding (RES) lines.
82 Amongst their findings, they observed very significant ice loss from beneath – much larger than the
83 rates identified in a recent modelling study by Bernales *et al*. (2017). Clearly then, there is much to
84 be gained from direct observations and measurements, and with that in mind, here we extend the

85 approach of Khazendar et al. (2016) to the GzIS and directly quantify spatially variable ice shelf
86 change.

87

3. Methods

89 In order to explore submarine change of the floating GzIS, repeat measurements are required of the
90 ice shelf surface and bottom. Such measurements are available from the Centre for Remote Sensing
91 of Ice Sheets (CRESIS) at the University of Kansas (Gogineni, 2012), and the radio echo sounding
92 (RES) data that they have gathered extensively across both Antarctica and Greenland using an
93 airborne system.

94 Initially, it was the Level 2 (L2) data which we looked to utilise, which provides measurements of ice
95 thickness as well as the elevations of the surface and bottom of the ice. However, we found a
96 number of anomalous points and so elected to go back to the Level 1B data from the Multichannel
97 Coherent Radar Depth Sounder (MCoRDS) – it is these data that are utilised and explored. The
98 benefit of using data from a lower processing level is that it enables picks to be verified or modified
99 first-hand. This RES system has been used to gather data since 1993 using funding from both NASA
100 and the NSF, most recently as part of the Operation IceBridge field campaign (Leuschen and Allen,
101 2014).

102 In November 2010, as part of the Operation Icebridge survey for this year, a flight took place over
103 the GzIS, closely following the linear ice-cliffs of the series of glaciers and ice-streams that drain into
104 the ice-shelf. As part of the Icebridge campaign of 2014, a section of the same survey line was re-
105 flown, again in November of that year (Figure 1). The MCoRDS radar data has an along-track
106 resolution of ~25 m and a depth resolution of ~ 18 m (Khazendar *et al.*, 2016). Using the Level 1B
107 data, each flight was re-examined for anomalous points (often associated with apparent incorrect
108 picking of the bottom reflector, or with inaccurate picking of the reflector) and these were
109 corrected. This was carried out using the Matlab code: 'image_browser_v1_4' available via the
110 CRESIS ftp site: ftp://data.cresis.ku.edu/data/picker/ (CRESIS, 2016), and corrected picks were then
111 compared.

112 Of course, despite these two flights covering effective repeat-tracks, individual sounding locations
113 are not exactly replicated between these four years. In order to maximise the usefulness of these
114 datasets, but also so as to not introduce artefacts, we followed the example of Khazendar *et al*.
115 (2016) and their recent work, by comparing points which are closer than 200 m in the horizontal.
116 Khazendar *et al*. (2016) imposed this limitation in order to reduce the effects of the slope of the ice
117 bottom when exploring change. An identical approach is followed here. The result of this analysis of
118 close overlap between the two survey flights (in 2010 and 2014) delineates the zone over which this
119 study takes place (see Figure 2). This zone covers a large part of the floating Getz ice shelf, and it is
120 this region on which the remainder of this paper is focussed (cf. Figure 1).

121 Once comparable points had been derived, the difference between the elevation of the underside
122 of the floating ice shelf was determined in each year, so as to explore the spatial variability in rates
123 of change at the ice shelf bottom.

124   The use of the MCoRDS radar to determine the ice shelf bottom does introduce some uncertainty,
125   not least because despite every effort to the contrary, flying repeated survey tracks four years apart
126   inevitably results in slightly different flight tracks and thus lightly different regions of the bed are
127   imaged. Figure 3 shows example radargrams from part of the repeated survey line in 2010 and 2014.
128   The region of the domain explored here is shown in green in Figure 2. Examination of Figure 3
129   reveals that despite the limitations indicated, remarkably good repeat-surveying has been achieved.
130   Only very slight differences are visible between these two sampled regions, as a result of slight
131   offsets in the two survey lines Khanzendar et al. (2016) go into some detail discussing how they
132   account for errors in the MCoRDS data. They suggest that based on system and environmental
133   parameters, a conservative estimate of vertical measurement uncertainty is ±25 m, while the
134   uncertainty in measurements of change between two years is ±35 m. However, they go on to say
135   that when considering annual rates of change in the base elevation, uncertainty is calculated by
136   dividing total change by the time between the two measurements (Khanzendar et al., 2016). As a
137   result, uncertainty estimates when comparing ice bottom changes between 2010 and 2014 is ±8.75
138   m a^{-1}.
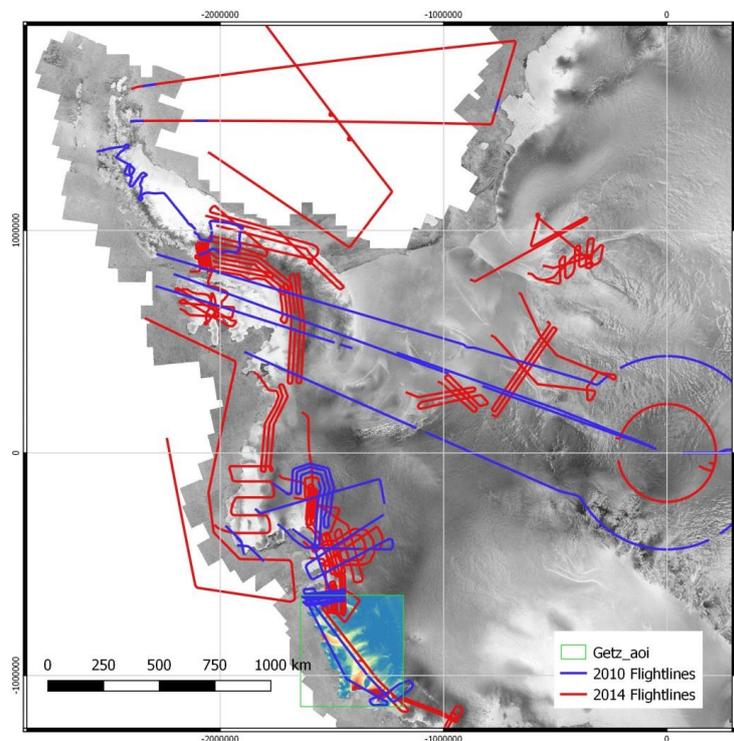
Figure 1: CRESIS flightlines across Antarctica in 2010 (blue) and 2014 (red). The focus of this study is located
towards the bottom of the image, and can be identified by the green rectangle and superimposed surface velocities
(Rignot et al., 2017; cf. Figure 3). The background image is the MODIS Mosaic of Antarctica (MOA; Scambos et al.,
2007; Haran et al., 2013; 2014). All data projected in polar stereographic coordinates.

139

140   In order to confidently identify 'real' changes at the ice-shelf base, it is important to assess if any
141   measured changes may actually be attributable to other erroneous factors (e.g. differences in
142   system parameters from one survey to the next; successfully picking the same basal reflector in both

143   surveys; resolution of the data). In order to do this, we firstly only utilise bed data where the pick-
144   confidence is high (as defined in MCoRDS data description). Furthermore, we also investigated basal
145   elevation change between the four years, focussing on grounded ice areas only. Here, there should
146   be a mean basal height change of zero (as there should be no basal change in grounded ice over this
147   timescale) with scatter around this representing the noise associated with slightly different flight
148   tracks and thus measured positions, as well as differences at the picking stage. We excluded extreme
149   outliers occurring due to gross errors (where differences exceeded 60 m, accounting for just 11.6%
150   of measurement samples), and investigated the relationship between the bed elevations in 2010 and
151   2014 in the remaining data. However, we did not treat all data points as one whole, since this simple
152   solution would assume a constant bias across the whole domain, taking no account of the potential
153   for different biases in different parts of the domain (e.g. a sloping bias). To that end, we explored the
154   differences in bed elevation in the four years in each of the five grounded zones independently.
155   From this investigation we discovered that the domain can be grouped into two regions which show
156   slightly different trends in bed elevation offsets between the two years. In the northern region, a
157   strong, systematic relationship between the bed elevations in 2010 and 2014 exists (R^2 ~1), with a
158   mean difference of +17.55 m, meaning that the 2014 bed is systematically higher than the 2010 bed.
159   In the southern region, there is also a strong, systematic relationship (R^2 of ~1), with a mean
160   difference of +28.73 m, again meaning that the 2014 bed is systematically higher than the 2010 bed
161   here, but by a slightly greater amount. These very strong systematic discrepancies mean we used
162   this information to correct all samples (not just grounded regions) to account for this bias, treating
163   the northern and southern regions differently.

164   Once debiased, we spatially average the along-track height change over samples within a 100m
165   along-track window size. We did this because we observed substantial variability in the bed
166   topography and spatially averaging reduces noise and helps to identify any outliers.
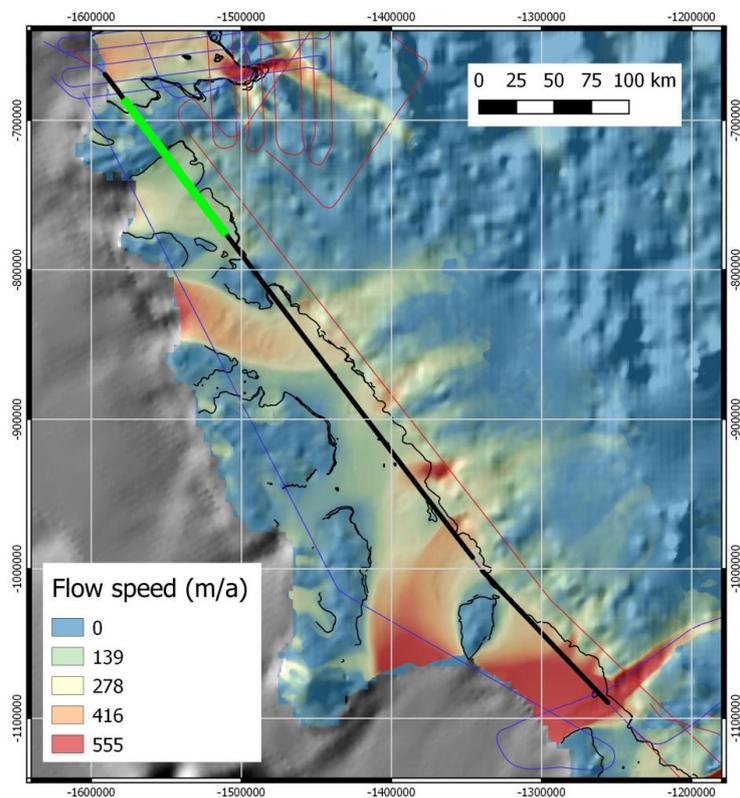
Figure 2: Close-up of area of interest over the Getz Ice Shelf. The thin blue and red lines indicate the IceBridge flightlines from 2010 and 2014 respectively. The thicker black line represents the area of overlap and the data on which this study is focussed. The portion of this black line that is coloured green represents the area covered by the sample radargrams in Figure 3. The thin black line represents the grounding line (Rignot et al., 2011; 2014; 2016). The background (grey-scale) image is a hill-shaded relief map derived from the BEDMAP-2 product (Fretwell et al., 2013). The red/white/blue shaded superimposed background displays surface velocities (Rignot et al., 2017).

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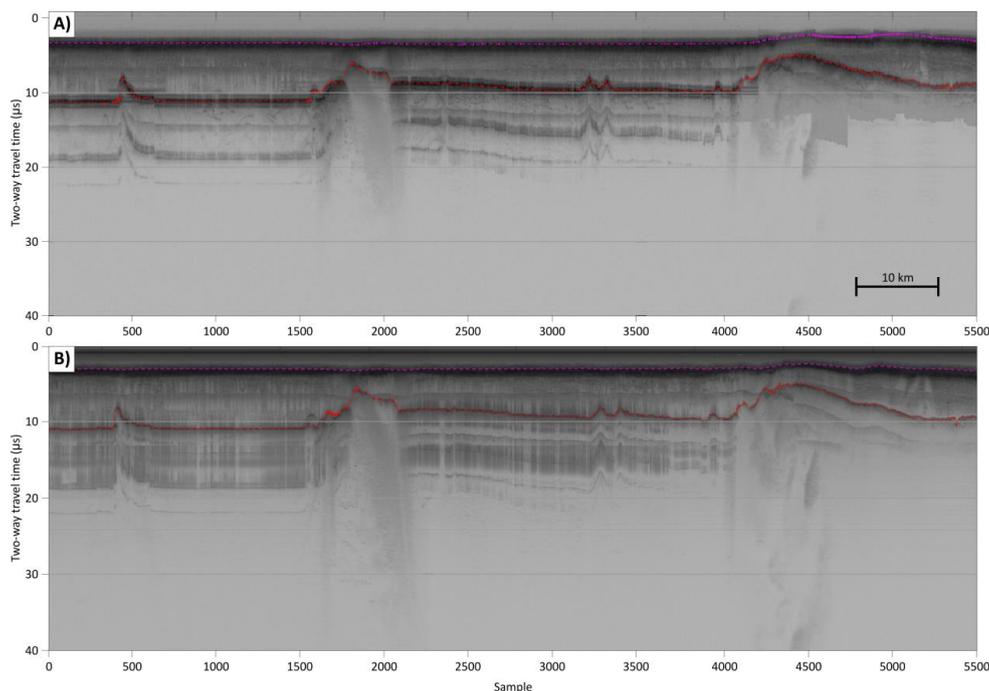
Figure 3: Example radargrams from the Operation Icebridge surveys of November 2010 (A) and November 2014 (B). These two sections represent repeat surveys over the area marked in green in Figure 2. It can been seen here that the two surveys achieved remarkably good repeated sampling locations, although subtle offsets and differences are visible, indicative of slight offsets in the two survey lines. The red dashed lines in both (A) and (B) represent the picked bed while the pink dashed lines represent the picked surface. In both cases, these are the picks provided by CRESIS, with small modifications and corrections made by the author (see main text).

168

169   In addition to investigating changes in the ice shelf bottom, we also investigated changes at the ice
170   surface. This was done using laser altimetry data that were collected on board the survey aircraft at
171   the same time as the RES data (Studinger, 2018). Data were gathered by the IceBridge ATM
172   (airborne topographic mapper) sensor at a spatial resolution of 80 m (sample width) and with a 40 m
173   along-track sample-spacing (Studinger, 2018). However, simply ascertaining changes in surface
174   altitude is not sufficient for understanding and assessing overall change at the surface in Antarctica,
175   because variability is also partly a consequence of changes within the firn layer, which can vary
176   widely (Ligtenberg et al., 2011). As a consequence, in addition to measuring ATM-surface changes,
177   we also explore the role of changes in the firn layer using output from the Regional Atmospheric
178   Climate Model (RACMO2; Ligtenberg et al., 2011). The model was run from January 1979 to
179   December 2015, and over this time period, surface height change was assumed to be zero (in
180   agreement with the model assumptions of steady state over the 35 years of the model run;
181   Ligtenberg et al., 2011). Changes in the firn layer (dH/dt_$firn$) between November 2010 and
182   November 2014 were extracted from the model output, and these were subtracted from observed
183   surface changes from the ATM (dH/dt_obs). This final, resultant change in surface elevation
184   (dH/dt_ice) is then attributable to a mass loss at the surface due to melt (or thickening due to
185   accumulation). Dynamic processes are also not accounted for, and are discussed later. Any
186   uncertainty in the firn model used to calculate surface change arises from uncertainties in
187   determination of accumulation and snowmelt in the initial spin-up stages of the model (Ligtenberg,
188   personal communication, 2017). Estimates of uncertainty in accumulation are 0.004 m yr^{-1} (% Acc)$^{-1}$,

189   whereas there is an estimated 20% uncertainty in snowmelt quantity. Taken in combination, the
190   greatest uncertainties occur in areas of greater melt (e.g. up to 0.15 m yr^{-1} on the Antarctic
191   Peninsula) while the smallest uncertainties are in cold interior regions (< 0.0001 m yr^{-1}) (Ligtenberg,
192   personal communication, 2017; cf. Pritchard et al. 2012). Again, for investigating change in the
193   elevation of the ice shelf surface, we follow the example of Khanzendar *et al.* (2016) and only
194   compare points in the different years that fall within the smaller distance of 25 m of each other.
195   Khanzendar *et al.* (2016) state that the uncertainty inherent in these ATM measurements is <0.09 m
196   (Krabill et al., 2002), but that where ice is afloat the effects of tides adds additional uncertainty of
197   0.4-0.6 m (Padman et al., 2002). As a result, we take a conservative error uncertainty of 0.7 m over
198   the four-year study period, neglecting all apparent measures of change that are less than this, but
199   annually this equates to 0.175 m/yr.

200   We utilise all of the datasets outlined above to examine the change in ice shelf thickness of the GzIS
201   between 2010 and 2014 and thus provide the first direct quantification of change at this ice-shelf.

202

4. Results and analysis

4.1. Changes at the ice-shelf surface

205   Before considering changes occurring at the base of the GzIS, it is important to recognise that total
206   ice thinning can be considered as the sum of changes taking place at both the top and bottom of the
207   ice-shelf. In order to extract thinning that is occurring as a consequence of basal melting, it is
208   necessary to constrain the contributions that come from changes taking place at the surface
209   (Khazendar et al., 2016). As described in the methodology, we constrained this by considering
210   observed changes from repeat ATM measurements in the domain, and by considering modelled
211   changes in the firn layer. The resultant changes therefore represent changes due to melting or
212   accumulation. In order to constrain the importance of surface changes on overall mass loss, we
213   focussed further attention only on slow moving areas which are grounded. The reason for this is that
214   it is in such regions that it can be assumed that the contribution to overall thinning at the base is
215   zero (because there is no basal melting where the ice is grounded) and the contribution to overall
216   thinning from dynamic processes is minimal. Table 1 summarises the findings of this analysis.

	Min	1st Quart	Median	Mean	3rd Quart	Max
All change	-1.946	-0.712	-0.165	-0.367	0.006	0.814
Rising surf (+ve change)	0.175	0.199	0.231	0.270	0.289	0.814
Lowering surf (-ve change)	-1.946	-1.085	-0.733	-0.775	-0.452	-0.176

Table 1: Summary statistics of the magnitude of annual change (m a^{-1}) at the ice surface elevation between 2010 and 2014 in areas of slow-moving grounded ice (cf. Figure 4). Surface elevation change (dH/dt_*ice*; m a^{-1}) is derived from measurements of repeated ATM observations (dH/dt_*obs*) and changes in the firn layer (dh/dt_*firn*) from the RACMO2 model (Ligtenberg et al., 2011). Data are subdivided into regions where the ice surface is rising (positive change) or lowering (negative change).

217

218   In this region, where changes are greater than uncertainties, 87.35% of point locations (746 of 854)
219   experiences surface lowering, with just 12.65% of locations (108 of 854) experiencing thickening. In
220   the small number of areas where thickening has occurred, the mean rate is nearly three times less
221   than where thinning has occurred. However, overall, these values are small, particularly when
222   compared with changes at the bed (cf. Table 3, but discussed later). Nevertheless, there is variability

223 in rates of accumulation (or otherwise) and we suggest that this variation can be explained by
224 altitudinal effects. The mean altitude where thinning takes place is 308.9 m whereas where
225 thickening dominates it is 504.2 m. Khazendar et al. (2016), in their work on the Dotson and Crosson
226 Ice Shelves, also found such altitudinal-controlled variability, suggesting that the relative role and
227 importance of air temperature, accumulation rate, as well as other factors that are influenced by
228 surface elevation change, might vary, and thus explain why mass loss or gain at the ice surface might
229 be experienced across the domain. Where they identified surface lowering (our dominant signal),
230 this was in the range of 0.4-0.7 m a^{-1}, and the values we record here are in very close agreement
231 with these.
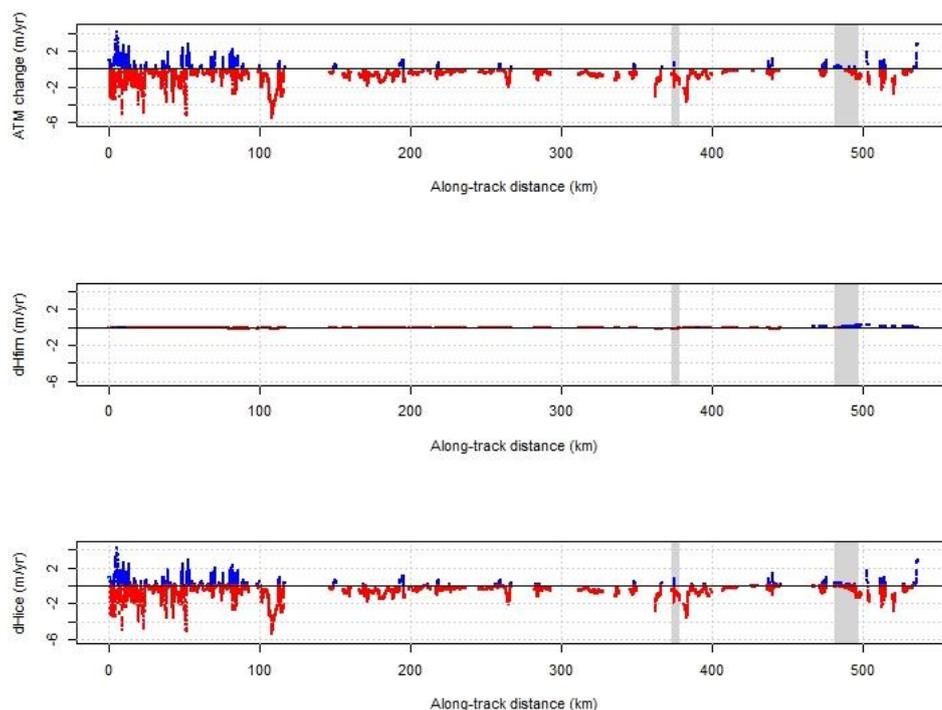
Figure 4: Annual change in ice-surface elevation (m a^{-1}) between 2010 and 2014 along the entire survey domain. The upper panel shows rates of surface change as derived from the repeat ATM measurements. The middle panel shows rates of surface elevation change based on changes in the firn layer, as derived from the RACMO2 firn densification model (FDM). The lower panel shows the residual change in surface elevation after considering firn densification processes. These changes are attributable to a mass loss due to melt. In all panels, blue dots indicate a positive elevation change meaning a rising ice surface and thus a thickening, while red dots indicate a negative elevation change meaning a lowering ice surface and thus a thinning. The black horizontal line represents no change. Grey shaded areas indicate where ice is slow-moving and grounded and thus minimal change would be expected. With reference to Figure 2, zero along-track distance in the above panels is associated with the southern-most points in the transect.

232

4.2. Changes at the ice-shelf bottom

234 We initially explored the annual rate of basal change along the whole survey-line from 2010 and
235 2014, but then subsequently subdivided the domain into those regions which we classify as being
236 within a floating ice-shelf, and others classified as being grounded (Figure 5).
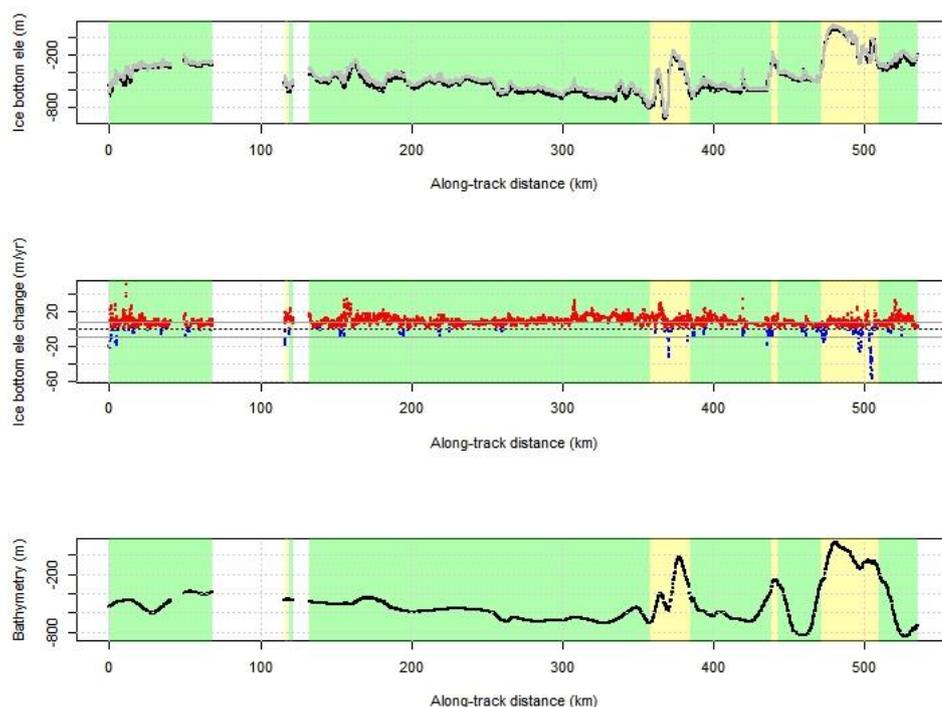
Figure 5: Annual change in ice-base elevation between 2010 and 2014 along the entire survey domain, with the 2014 bed elevations debiased according to the methodology described. The upper panel shows how the ice-bottom has changed between 2010 and 2014. The black line represents the bottom in 2010 and the grey line in 2014 (debiased). Data shown here are raw bed elevations. In the second panel, rates of bottom elevation change (m a^{-1}) are shown, with elevation change spatially averaged over 100m-long windows. In the middle panel, red dots indicate a positive elevation change meaning a rising ice bottom and thus ice-shelf thinning. Blue dots indicate a negative elevation change meaning a lowering ice bottom and thus ice-shelf thickening. The grey horizontal lines represent the bounds of uncertainty – values must indicate changes of magnitudes greater than these limits to be indicative of real change (see text). The lower panel indicates the bathymetry of the sea-bed at each point derived from the International Bathymetric Chart of the Southern Ocean (IBCSO v1.0; Arndt et al., 2013). Areas with a green background are areas where floating ice-shelves are present. Areas with a yellow background are where ice is grounded (cf. Figure 2 for location of survey domain). Note the significant data-gap between ~75-120 km along track. Here, bed picks are of lower confidence in one or both of the two surveys, and so data here is not included to avoid introducing erroneous measurements of change.

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238   In Figure 5, a positive change reflects a rising of the ice-base and thus thinning and mass loss.
239   Conversely, a negative change reflects a lowering of the ice-base and thus a thickening or mass gain.
240   Perhaps the most important panel in Figure 5 is the middle panel because this indicates the overall
241   amount of change at the ice-shelf bottom. Red symbols in this panel (in Figure 5) represent a rising
242   ice-bottom, and where this change reaches beyond the margins of error (grey horizontal lines in
243   these panels) then we consider this rising ice-bottom to be real. It can also be seen that in some
244   locations (where blue symbols are visible) the ice-base has lowered. These locations are more
245   sparsely distributed, but nevertheless it is important to consider where these areas of apparent ice-
246   bottom lowering (and indeed rising) are located.

247   Of all the spatially-averaged sample points along this line (5357 in total), 71.46% are classified as
248   being within floating ice shelves, while 7.62% are associated with grounded ice (the remaining
249   20.93% are generally associated with no data (due to the exclusion of low-confidence picks). Where

250   picks are high quality however, 90.37% (3828) are classified as being within floating ice shelves,
251   while 9.63% (408) are associated with grounded ice.

252   Considering floating and grounded ice together, 4350 (81.20%) show a rising of the ice-base (and
253   thus thinning) with just 299 (5.58%) indicating a lowering of the ice base (and thus thickening).
254   However, many of these points are within the error margins of ±8.75 m discussed previously – only
255   48.04% of all points show any sort of change larger than the margins of uncertainty. Of these points
256   alone, 82.75% are within floating ice shelves and just 10.86% are within grounded ice. Table 2
257   summarises the changes that have taken place where the observed change is greater than the
258   uncertainty.

259

	No. of points	% of total
Total number of samples	2035	100 %
Ice shelf – rising base (thinning)	1668	81.97 %
Ice shelf – lowering base (thickening)	16	0.79 %
Grounded ice – rising base (thinning)	195	9.58 %
Grounded ice – lowering base (thickening)	26	1.28 %

Table 2: Summary of changes at the ice-base where spatially-averaged changes are greater than the suggested error of
±8.75 m. The table shows the number of points and also the relative dominance of each class as a proportion of the total
number of sample points where change is larger than uncertainty. The data is split into areas of floating ice-shelves and
grounded ice, as well as being further subdivided into areas where the apparent change is positive (i.e. meaning a rising
ice base and thus thinning) or negative (i.e. a lowering ice base and thus thickening).

260

261   Table 2 shows that it is on the floating ice-shelves where change at the base is of greatest
262   significance, and apparent rising of the ice base is the dominant signal (81.97% of all points where
263   change is greater than errors). On the ice-shelf alone, positive change (i.e. thinning of the base) is
264   apparent in 99.05% of all ice-shelf measurements that are greater than errors. In just 0.95% of cases
265   ice shelf thickening is apparent. Table 3 shows the magnitude of the changes taking place in these
266   floating-ice regions. It is important to note that the changes at the base here are two orders of
267   magnitude greater than those at the surface (cf. Table 1) rendering the changes and uncertainties at
268   the surface almost irrelevant by comparison. Clearly then, while there is some spatial variability,
269   significant thinning of floating ice is the dominant signal in the domain.

	Min	1st Quart	Median	Mean	3rd Quart	Max
Thinning (+ve change)	8.75	9.99	11.66	12.85	14.58	52.24
Thickening (-ve change)	-21.61	-17.92	-14.13	-14.23	-9.31	-8.90

Table 3: Summary statistics of the magnitude of change (m a^{-1}) at the ice base in floating ice-shelves where change is greater
than the measure of uncertainty (±8.75 m). Data are subdivided into regions where the ice-shelf base is thinning or rising (positive
change) and where it is thickening or lowering (negative change). Note that although the magnitude of mean thickening is greater
than the thinning, thickening takes place over a much smaller number of measurement locations.

270

271   With respect to the thickening regions of floating ice shelf (where greater than errors), although
272   these regions are relatively sparse, close analysis of bathymetry data from the International
273   Bathymetric Chart of the Southern Ocean (IBCSO v1.0; Arndt et al., 2013; cf. bottom panel of Figure
274   5) suggests that they may arguably be most prominent where the bed topography is most variable
275   (e.g. at ~0-75 m along-track and ~420-430 m along-track). In such regions, slope-changes are larger,
276   perhaps reflecting locations where floating ice abuts grounded ice, and thus inaccuracies in

277 delineating the boundary between these two are apparent. We consider this further in the
278 discussions.

279 Figure 6 shows the distribution of the magnitude of ice-base thinning and thickening (where
280 measurements are greater than uncertainty), while Figure 7 shows where the greatest amount of
281 ice-bottom melting has taken place. Figure 6 clearly demonstrates that the greatest signal is one of
282 ice-base thinning in floating ice, and that overall, an annual ice-base loss of ~10-20 m a^{-1} is most
283 common, with a few areas experiencing losses of 2-3 times this.
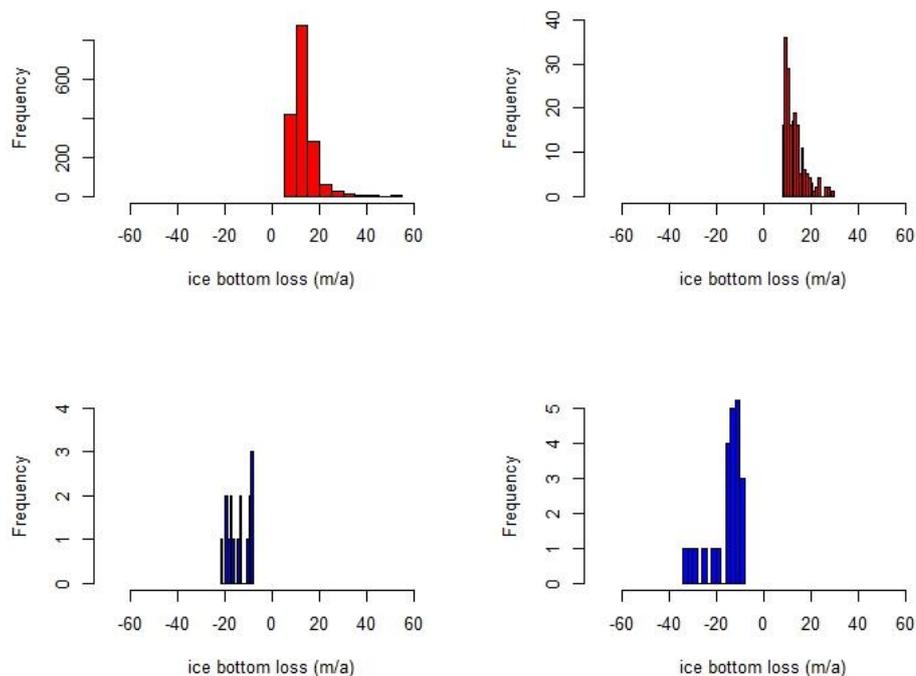
Figure 6: Histograms showing the amount of ice-bottom change experienced where the ice is floating (left-hand panels) and where it is grounded (right-hand panels), with thinning displayed in red in the top two panels, and thickening displayed in blue in the bottom two panels (only where greater than uncertainties). Where ice bottom loss is positive, this represents thinning between 2010 and 2014. Where ice bottom loss is negative, this represents thickening between 2010 and 2014. Note the markedly different y-axis scales. It is very clear that thinning dominates, and that this thinning is much more pronounced and widespread where the ice is afloat.

284

285 Figure 7 shows the locations where these losses are at their greatest and it can be seen that in
286 general there is a tendency towards greater ice loss in locations where the ice is fastest flowing (left-
287 hand panel). In slower-flowing regions, changes are perhaps smaller. This relationship suggests there
288 may be a dynamic thinning component, in which some ice loss occurs due to dynamic processes. This
289 is dealt with further in the Discussions.

290
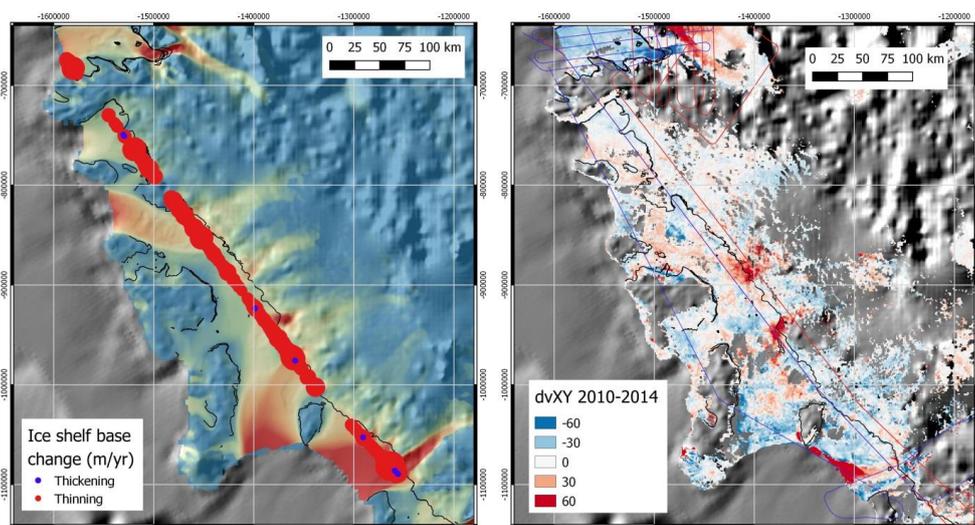
Figure 7: Left-hand panel shows ice shelf thinning (red circles) and thickening (blue circles) where change is greater than the margins of uncertainty, and only where ice is floating. Ice loss (thinning) is greatest where ice velocities are higher. The black line represents the grounding line (Rignot et al., 2011; 2014; 2016). The background (grey-scale) image shows bathymetry data from the International Bathymetric Chart of the Southern Ocean (IBCSO v1.0; Arndt et al., 2013). The red/white/blue shaded superimposed background displays surface velocities with red regions indicating fast flow and blue areas indicating slow flow. (Rignot et al., 2017). In the right-hand panel, changes in surface velocity are displayed, derived from the MEaSUREs Annual Antarctic Ice Velocity Maps 2005-2016 (Mouginot et al. 2017). Here we display the difference between two datasets, one of velocities from 2010-2011 and another from 2014-2015.

291

292   Where changes are apparently occurring at the base of grounded ice, it is important to keep in mind
293   that all change in grounded regions accounts for a relatively small proportion of those sampled
294   locations (10.86% of all data; Figure 6; cf. Table 4). Nevertheless, it is important to note that the
295   apparent changes here are not insignificant.

	Min	1st Quart	Median	Mean	3rd Quart	Max
Thinning (+ve change)	8.75	9.92	12.10	13.14	14.69	29.43
Thickening (-ve change)	-33.09	-15.09	-12.89	-15.30	-10.84	-8.88

Table 4: Summary statistics of the magnitude of change (m a⁻¹) at the ice base in regions of grounded ice where change is greater than the measure of uncertainty (±8.75 m). Data are subdivided into regions where the ice-shelf base is thinning or rising (positive change) and where it is thickening or lowering (negative change).

296

297   Such change under grounded ice is somewhat surprising, since, at the ice base, it would be expected
298   that there would be no such change – at this location, over the timescale being explored, the ice
299   base should effectively be static. However, we propose that this apparent change is in fact not
300   indicative of real change, but is in part a function of an uneven (or rough) subglacial topography in
301   which correct identification of the bed reflector is not straightforward and is indeed prone to errors.
302   Under scenarios where a complex bed topography dominates, both along-track and off-track, it is
303   highly likely that the bed is incorrectly picked between consecutive years (cf. Lapazaran et al., 2016).
304   Indeed, we encountered this in our own investigations and adapted our methodology to go some
305   way towards incorporating this (see Methods). It is also highly likely that precisely the same track is
306   not taken between surveys, further introducing errors. Finally, a relatively large component in the
307   error is likely a result of uncertainties in the aircraft flying height during data collection. In some

308 locations however, such discrepancies may be due to real changes, which will be discussed further in
309 the discussions.

310

311 **5. Discussions and Conclusions**

312 For a long time, the main cause of mass loss from the Antarctic Ice Sheet was considered to be
313 iceberg calving (Depoorter et al., 2013). More recently, melting of floating ice due to a warming
314 ocean has been shown to be significant, particularly close to the grounding line and near the calving
315 front (Jenkins and Doake, 1991; Rignot and Jacobs, 2002; Joughin and Padman 2003). However,
316 direct measurements of basal ice shelf change in Antarctica are sparse. While Khazendar et al. (2016)
317 were the first to show direct evidence of ice-shelf thinning from repeat RES measurements, here we
318 have presented the first direct measurements of ice shelf change on the large GzIS using repeated
319 airborne RES surveys. Comparison of the recent modelling output from Bernales *et al*. (2017) with
320 the measurements of Khazendar *et al*. (2016) shows that the models underestimate the amount of
321 basal melting, and given that it is the Amundsen Sea (including the GzIS) where greatest changes are
322 forecast to happen in the decades to come (Naughten *et al*., 2018), assessing whether such
323 discrepancies exist here is of importance. As a result, we have investigated the magnitude and
324 nature of change at both the surface and the base. When exploring surface changes, we found that
325 these are small compared to those observed at the bed, by up to two orders of magnitude, and thus
326 in this study over the GzIS, surface lowering can, to all intents and purposes, be ignored. The
327 changes taking place at the ice base are far greater and far more significant, and so it is therefore
328 this location where we focus the remains of this discussion.

329 In terms of basal changes, floating ice dominates the domain, and it is here that changes are of
330 greatest magnitude, of greatest interest and also of greatest significance. Where ice is floating and
331 where changes are significant, thinning was observed in nearly 82% of locations, at a mean rate of
332 nearly 13 m a^{-1}, but up to a maximum of ~52 m a^{-1}. These values are (on average) slightly smaller
333 than, but nevertheless comparable with, the 40-70 m a^{-1} recorded by Khazendar et al. (2016) the
334 Dotson and Crosson ice shelves. Furthermore, the rates of change that are identified here are
335 substantially greater than those reported by Bernales *et al*. (2017) in their extensive modelling study
336 of basal changes around Antarctica. Their model suggests melting rates of 2.5 / 4.3 m w.e. a^{-1}
337 (equilibrium/non-steady state values) which are several times lower than our measurements. The
338 identification of substantially higher rates of loss is of great concern because it means it is losing
339 mass more quickly than previously thought, with significance for the rates at which ice is transmitted
340 through the glaciers which drain into the GzIS. While thinning occurred over most of the domain, the
341 biggest rates of thinning occurred where ice flowed more quickly (cf. Figure 7) perhaps also
342 indicating a role for dynamic processes in the observed thinning. Dynamic thinning is a loss of ice as
343 a result of accelerated flow (Pritchard et al., 2009). While not a true measure of dynamic thinning
344 itself, increasing ice flow may lead to the dynamic thinning of a glacier (Bevan et al., 2015), and so by
345 assessing changes in ice velocity (as well as velocity itself), the relative likely importance of the
346 dynamic thinning process can be ascertained. The observations we make are thus further reinforced
347 by Chuter et al. (2017) who identified variable rates of grounding line velocity increases (2007-2014),
348 but particularly a coincidence between the largest grounding-line velocity increases and regions of
349 greatest ice-shelf thinning (Chuter et al., 2017; their Figure 4). We therefore suggest that some of

350 the observed thickness change on the GzIS may be attributable to dynamic processes rather than
351 direct mass loss at the bottom (or indeed the surface) of the ice-shelf.

352 Changes greater than uncertainty over grounded ice accounts for approximately 10.86% of the
353 survey domain. Where ice is grounded, the complex subglacial topography makes it difficult to
354 accurately pick the terrain, and as a result, there is some uncertainty surrounding the basal
355 variability. However, in ~13% of locations we observe apparent shelf thinning over grounded ice, and
356 it is possible that some of this apparent thinning may be attributable to ice-shelf ungrounding
357 between the two surveys. We have no evidence of this having occurred but Schaffer *et al*. (2016)
358 propose the existence of continuous troughs that link the open ocean to the grounding line, and
359 propose that high basal melt rates here support the existence of a routeway along which warm
360 ocean waters may access the ice base. This proposal, though untested would perhaps allow melting
361 of grounded ice at the grounding line, and thus a degree of ungrounding, as we propose.

362 Our work highlights firstly, and crucially, that thinning is both significant and widespread across
363 much of the GzIS. Secondly, it highlights that despite this, there is significant variability in ice-shelf
364 bottom change, reinforcing the point made in the *Introduction* that ice shelf complexity has an
365 important role to play in controlling the way and rate by which an ice-shelf responds to oceanic
366 warming. Finally, and perhaps most importantly, our work identifies substantially greater rates of
367 thinning than those recently reported from forecasting modelling investigations (Bernales *et al*.,
368 2017). While we accept that our work represents investigations along a single transect, the
369 difference between predictions from models and direct historical measurements (c.f. Khazendar *et*
370 *al*., 2016) is clearly of concern. This suggests that models may be underestimating changes going on
371 in at least some parts of some ice shelves, and thus more and continuous direct measurements of
372 change are required. This is firstly to help better constrain models, and secondly to better constrain
373 the changes actually occurring in ice shelves.

374 Depoorter et al. (2013) state that the significance of basal processes in overall ice shelf mass balance
375 is highly variable, accounting for 10-90% of overall loss, depending on the specific ice shelf in
376 question. Here, we have shown that basal melting is a significant contributor to mass loss of the
377 GzIS, but also that the relative contribution of basal melting is highly variable across the ice shelf.
378 This variability within a single ice shelf, coupled with the apparent variability between ice shelves
379 (Depoorter et al., 2013) is significant. In the GzIS, the variability can perhaps be attributed to the
380 combination of complex sub-ice topography and numerous contributory ice streams and outlet
381 glaciers that result in intricate sub-ice water circulation is cavity systems. Although the accuracy of
382 this interpretation requires further investigation, the importance of these processes in overall ice
383 shelf mass balance is undeniable. It, it is therefore of paramount importance that quantifying basal
384 mass loss from Antarctic ice shelves is carried out, because of its role and importance for predicting
385 the likely vulnerability of ice shelves to future subglacial warming and melting.

386

387 **6. Acknowledgements**

388 We acknowledge the use of data and/or data products from CReSIS generated with support from the
389 University of Kansas, NSF grant ANT-0424589, and NASA Operation IceBridge grant NNX16AH54G.

We also acknowledge Stefan Ligtenberg and Jan Lenaerts for the provision of (and assistance with) RACMO2 data.

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