

Author response by Tian Li on behalf of all the other authors:

We would like to thank the reviewers for their exceptionally detailed and constructive comments on our paper, which have proven very helpful in revising this manuscript. We have been able to fully address the suggested changes and we think the revised manuscript has been greatly improved. Our detailed responses to each comment presented by the reviewers are in blue text.

Reviewer 1

Review of “Mapping the Antarctic Grounding Zone from ICESat-2 Laser Altimetry” by Tian Li et al.

Li et al. use 12 months of observations from the newly launched ICESat-2 laser altimeter to recover two key components of Larsen C Ice Shelf’s grounding zone (GZ). Building upon the repeat-track methodology first applied to ICESat GLAS data (e.g. Fricker & Padman, 2006; Fricker et al., 2009; Brunt et al., 2010; 2011), the authors use elevation departures from mean tidal state to infer the landward limit of tidal flexure and point of hydrostatic equilibrium over successive repeat passes. By exploiting the beam-pair imaging capabilities of the ATLAS instrument on-board ICESat-2, the authors also apply a cross-track slope correction to their dataset, greatly improving the signal-to-noise ratio of GZ detection over areas of rough terrain compared with single-beam ICESat methods. Elevation changes derived from ICESat-2 ascending and descending cross-over passes are also used to approximate the position of the GZ (although at much degraded resolution c/w their repeat-track observations), thereby acting as a part-validation of their repeat-track-derived GZ picks.

Given the close agreement between ICESat-2 and independent InSAR-based GZ observations ($\sim\pm 0.5$ km separation, assuming no GL migration between acquisition dates) and the fact that this technique is fully automated, I believe that Li et al’s technique will be of large interest to the readership of *The Cryosphere*, and look forward to seeing this paper published. The prospect of applying this technique to the entirety of Antarctica’s grounding zone is also an exciting one. Before acceptance, however, I feel that moderate revisions must be implemented to improve the clarity and flow of the manuscript, and to address several technical points pertaining to the GZ detection technique and comparison with other data sources. My suggested revisions and other comments are included below.

This is a very good summary for the methods and results presented in our study and we would like to thank the reviewer for the detailed comments. We have now made the following changes to address the major comments from both the reviewers.

- i. We used the latest ATL06 version 3 data during a 10-month period between March 2019 to March 2020, including four repeat cycles (3, 4, 5 and 6) for both repeat track analysis and crossover analysis. The GZ results have been recalculated over the Larsen C Ice Shelf.
- ii. We have modified the reference GL used in repeat track analysis by merging the 2015-2016 ESA CCI DInSAR Point F (ESA Antarctic Ice Sheets CCI, 2017) and the Depoorter et al. (2013) GL.
- iii. We added the repeat track analysis for six individual ground tracks in addition to the repeat track analysis for beam pairs used in the previous submission. Although we do not expect a substantial across-track slope over a ~ 10 m separation for repeat tracks of each ground track, using beam pairs with the across-track slope correction is essential for high-sloping regions. As the example shown in Fig. 6, the ~ 10 m across-track separation can still lead to significant across-track slope induced errors in elevation change (Figs. 6a-6d), but the across-track slope correction can reduce this error (Figs. 6e-6h).

- iv. We have modified the crossover analysis by using the average elevation change at each crossover location, this removes a lot of noise observed in the previous data.
- v. We only compared the ICESat-2-derived Point F with ESA CCI DInSAR Point F, and removed the comparison between ICESat-2-derived Point F with Rignot et al. (2016) DInSAR GL and the ICESat-derived Point F (Brunt et al., 2010). We have also compared the ICESat-2-derived Point H with ASAIID Point H (Bindschadler et al., 2011).
- vi. We have modified the overall structure and the clarity of the paper, especially Sections 3 (Methodology) and 4 (Results and discussion).

General / Major Comments

While it's clear that the authors have invested a large amount of time and effort in the development of their GZ detection technique, I feel that large parts of the manuscript should be thoroughly edited by all authors to increase the overall clarity, flow and standard of English presented in the text. At present, the main text is at times highly verbose and/or repetitive, which – together with the use of non-standard sentence/paragraph structure throughout the manuscript – makes it difficult for the reader to easily follow the narrative of the paper. This is especially true in the methodology and results sections, where, for example, the reader must repeatedly flick back and forth between the discussion of Points F and H - this has the potential to be extremely confusing, especially to those unfamiliar with the anatomy of the GZ. As I outline in my specific comments, these sections could easily be restructured to offer a more streamlined discussion. I would also strongly encourage the authors to correct the numerous instances of incorrect grammar contained in their manuscript (I have indicated some, but not all instances of this in my specific comments).

We agree with the reviewer that we need to improve the overall clarity of the context. We have substantially modified the structure and language based on reviewers' comments and we believe the overall clarity, flow and the standard of English have now been greatly improved.

Lines 183-216 – To my knowledge, the 2017 ESA CCI dataset provides near-complete coverage of Larsen C's GL as constrained from Sentinel-1a/b DInSAR-based observations acquired in 2016/2017. I am therefore surprised to read that the majority of the ICESat-2- DInSAR comparisons made in this manuscript refer to the earlier (mostly 1990s ERS-1/2- based) GL products provided by Rignot et al., (2016), and not those more temporally contemporaneous with the authors' ICESat-2 observations.

We agree with the reviewer that it will be more useful to compare our results with the most up-to-date ESA CCI grounding line product. We have now removed the comparison between ICESat-2-derived Point F with the DInSAR grounding line provided by Rignot et al. (2016), and only compared our results with the ESA CCI DInSAR Point F. Please refer to line 12-15, line 276-288, line 360-362, Table 2, Figs. 7 and 10.

Furthermore, while the authors correctly mention in lines 106/107 that recent (2010-2016) GL migration has been fairly minimal, a comparison of the Rignot and ESA CCI products reveal large retreats (up to 4 km) along parts of Larsen C's GL (including Churchill and Kenyon Peninsulas), presumably in response to the sustained period of ice-thinning between 1979 and 2008 noted in the literature (Fricker et al., 2012, JGR: Oceans; Adusumilli et al., 2018, GRL). (NB. Since 2008, Larsen C has largely thickened, consistent with the more stable rates of GL migration reported by Konrad et al. (2018)).

This is a very good point. We use the fact that the grounding line on Larsen C Ice Shelf has been relatively stable during our observation period for two reasons. The first is for the comparison with DInSAR grounding line observations. Especially as we are now using the latest ESA CCI grounding line

product for comparison with the ICESat-2-derived Point F, we are confident that the grounding line migration has been very small between the two measurements. The second is to define a calculation window for our automated grounding zone detection algorithm. The 24 km calculation window for the reference GL, which was the Depoorter et al. (2013) GL in the initial submission, should be sufficient to capture the grounding zone within it, even including the ~4 km GL retreat between 2010 and 2016. Nevertheless, to avoid the uncertainty in the location of the Depoorter et al. (2013) GL which was derived from a composite of outdated GL products, we have now modified the reference GL by merging the 2015-2016 ESA CCI DInSAR Point F and the Depoorter et al. (2013) GL (line 120-129).

As such, I believe making primary reference to the old Rignot GL dataset is inappropriate in this context, and would strongly suggest the modification of the abstract, lines 183-216, discussion/conclusion and Figures 2, 5, 6 and 7 to refer only to the newer ESA CCI GL. Also, be sure to include the appropriate citation for the ESA CCI dataset in the reference list.

Agree, we have now removed all the comparison with the Rignot DInSAR GL dataset and only compared ICESat-2-derived Point F with ESA CCI DInSAR GL. We have changed the correct citation for the ESA CCI dataset in the reference list into 'ESA: Antarctic Ice Sheet Climate Change Initiative, Grounding Line Locations for the Fleming and Larsen Glaciers, Antarctica, 1995-2016, v1.0, Centre for Environmental Data Analysis, 2017.'

Technical Comments

Line 71 and Figs 5 and 7 – The authors mention the use of data from repeat cycles 3-5 in their repeat track analyses, but Figures 5 and 7 only show the solution as derived from repeat tracks 3 and 4. Why is this? For consistency with the main text, I'd update Figures 5 and 7 to show the full complement of data acquired over the entire range of images tidal states.

Agree, we have modified the Fig. 5 to include all the repeat cycles (3, 4, 5 and 6) used in this study to show the full tidal range.

Line 102 – As the authors know, the Depoorter GL is a compilation of multiple GL datasets, derived from a variety of techniques (e.g. InSAR, break-in-slope, ICESat) applied to satellite imagery acquired at different times. For absolute clarity here, I'd consider adding an overview of the imaging times and techniques used over this region of Antarctica.

Agree and done. We have modified the reference GL by merging the latest ESA CCI DInSAR GL (2015-2016) with the Depoorter et al. (2013) GL to avoid the uncertainty of the GL location in the calculation (line 120-129). An overview of the imaging times and techniques used in Depoorter et al. (2013) GL has also been added in line 120-129.

Lines 120-125 – For clarity, I suggest defining each of the terms included in Eq. 1 before discussing Eq. 2. Also note the lack of any explicit definition of $Y_{ATC,G}$ in the current version of the manuscript.

Agree and done. $Y_{ATC,G}$ is the y coordinate measured perpendicular to the Reference Ground Track (RGT). For clarity, we have now changed $Y_{ATC,G}$ to Y_L (y coordinate measured perpendicular to the RGT for the left beam in a pair) to demonstrate the across-track slope correction from left beam to the nominal reference track in the middle of the beam pair (Eq. 1 and 2).

Lines 136-160 – In Figure 1 the authors show the position of I_b , the ice-sheet-shelf inflexion point (otherwise known as the break-in-slope), which is obtainable from optical-, DEM- and altimetry-based

methods. As the authors are aware, I_b has been used extensively in the literature (including Christie et al. (2016) as mentioned in the text, but also e.g. Bindschadler et al. (2011, *The Cryosphere*) and Scambos (2007, *Remote Sensing of Environment*)) to supplement our understanding of the GZ in areas where DInSAR coverage is poor. I was therefore a little surprised to see no discussion or method of deriving this important GZ component using ICESat-2 in the text. This is despite the break-in-slope being clearly visible in e.g. Figures 5a and 5c. Was any attempt to automate this component of the GZ made? If not, why not? I think a brief discussion of I_b , its manifestation in the ICESat-2 data and any attempts to automate it should therefore be added to the Section 3.1. If easily obtainable, then an additional figure similar to Figure 5c could also be added to show any differences in ICESat-2-derived I_b and the break-in-slope mapped by ICESat-1 (Brunt et al., 2011) and/or the ASAIID team (Bindschadler et al. 2011).

We have now explained the definition of Point I in line 33 and the previous research on identifying Point I in line 48-50. We agree that the break-in-slope can provide reliable representation for the grounding line in slow-moving regions, but this method is less effective in identifying fast flowing glaciers with low surface slope (Bindschadler et al., 2011; Scambos et al., 2007). The identification of Point F based on tidal flexure, however, is not influenced by these limitations. Also, the method developed in this study is based on detecting the changing points from the elevation anomalies rather than the surface slope, this cannot be directly applied to the identification of Point I. While our method could potentially be modified to detect Point I, it is beyond the research scope of this study.

On a related note, I have noticed occasional large errors in the positioning of DInSAR-derived GLs (Rignot, ESA CCI) over the Antarctic Peninsula (including Larsen C), presumably related to the geocoding of SAR data over the Peninsula's steep terrain using old DEMs, and/or the misattribution of the Point F on ice landward of nunataks or other mountainous exposures at the GZ. These positional errors are not seen in e.g. the ASAIID product due to the on-nadir viewing angle of Landsat and the ability to distinguish between mountains and ice more easily. Therefore, any comparison of ICESat-2- and ASAIID-derived I_b picks may be more representative of the true GL (in lieu of Point F) in these areas. (As a relatively slow flowing region with a well-defined break-in-slope, I_b will fall close to Point G (as it does in Fig. 5), making it reliable proxy for Point G and F).

In light of the above and if not already done, the authors should thoroughly QC the DInSAR product for such offsets – their omission could actually improve your mean absolute separation statistics!

We have now compared our ICESat-2-derived Point F with ASAIID break-in-slope point (line 282-288) and added a new figure (Fig. A1 in Appendix A) to show the spatial distribution of absolute separation. The result shows a close agreement between the two products, with an absolute mean separation of 0.34 km and a standard deviation of 0.28 km (Table 2). The overall separations in Churchill and Kenyon Peninsula are smaller than the DInSAR-derived Point F (Fig. 7c).

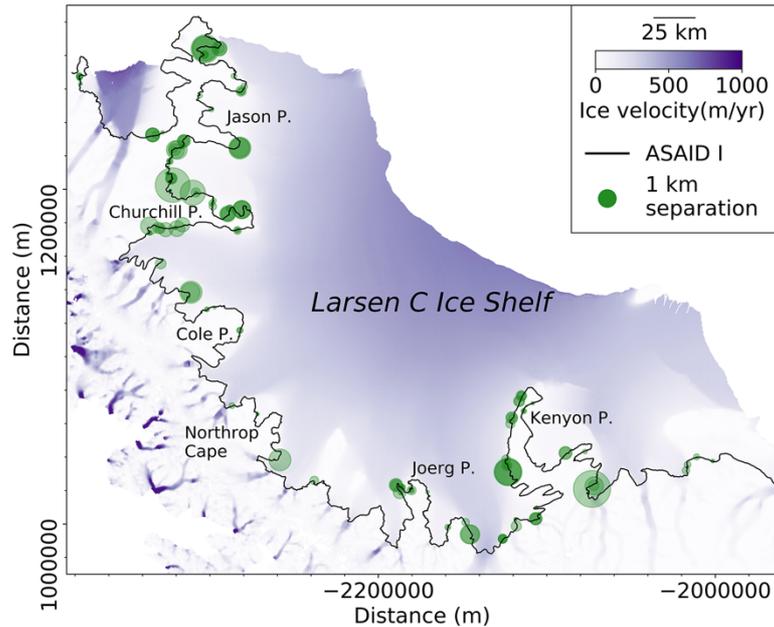


Figure A1. Absolute separations between ICESat-2-derived inland limit of tidal flexure (Point F) and ASAIID break-in-slope point (Point I). ASAIID Point I is shown as the black line (Bindschadler et al., 2011). Background is the recent ice surface velocity magnitudes (Rignot et al., 2017) in Antarctic Polar Stereographic (epsg:3031) projection.

Lines 150 and 156 – How sensitive is the pinpointing of Point *H* to the prescribed variance threshold used in the error function, and why was the fourth derivative of this function chosen? In other words, how would e.g. a 3rd order fit look on Figure 5d, and where would *H* be placed as a result? Some discussion of your choice is needed in the text here.

We have now discussed the reason of choosing the fourth derivative of the Error function as a guide point in searching for Point *H* in line 179-184 and Fig. 5d. The vertical dashed grey line in Fig. 5d shows the position of Point *H* if using the same guide point for Point *F* (third derivative of the Error function). It is clear that this location is slightly landward compared to the actual Point *H* signal (the vertical dashed blue line).

Line 190 – With the exception Churchill Peninsula (Figure 6a) where ***one*** ICESat-1 *F* point falls very close to the ICESat-2 *F*, spatially coincident ICESat-ICESat-2 observations do not exist anywhere else along the Larsen C coastline. I would therefore excise any comparison between the two datasets from the text as I don't think such statements can be made with confidence. Instead, I'd solely report on the close agreement between ICESat-2 and DInSAR observations. (the discussion of the enhanced coverage between ICESat-1 and ICESat-2 is okay, however!).

Agree and done. We have now removed all the spatial comparison between the GZs derived from ICESat and ICESat-2, and only kept the discussion on the enhanced density of ICESat-2-derived GZs compared to ICESat in line 249-251.

Sentence beginning line 196 – The GZ information contained in Dawson and Bamber (2017) refers to Siple Coast, not Larsen C. Are the reported separation values mentioned in the text derived from those observations over the Siple coastline, or has the methodology of Dawson and Bamber been extended to Larsen C? This is essential information to state here.

The reviewer is correct that the GZ information contained in Dawson and Bamber (2017) only refers to Siple Coast on Ross Ice Shelf rather than Larsen C Ice Shelf. However, they have extended their methodology to Larsen C Ice Shelf in a most recent paper (Dawson and Bamber, 2020), and reported a standard deviation of 1.2 km between CryoSat-2-derived Point F and ESA CCI DInSAR Point F. Therefore, we have modified this argument to only include the comparison in the same region by Dawson and Bamber (2020) in line 279-280.

Lines 217-226 – In Figure 8 (b and c especially), I see numerous instances of dark blues over the ice shelf which, following the main text, readers might incorrectly interpret as grounded ice. The opposite is true over grounded ice, which may be interpreted to be floating. What is the explanation for these observations? Surface processes? A few sentences explaining these blips are essential here.

Agree. For the crossover method, we now use a 10-month period of ATL06 version 3 data from 30 March 2019 to 6 March 2020 in order to be consistent with the repeat track analysis (line 65-70). We have also modified the crossover analysis by using the average elevation change at each crossover location (line 245-246), this removes a lot of noise observed in the previous data. To demonstrate the advantage and potential of crossover analysis, we have modified the figure to include the distribution of crossovers $|dh|$ on Hearst Island (now Fig. 9), where the crossovers show a very obvious transition from land ice to floating ice (line 305-319).

Lines 233-235 – Similar to my comments on the potential derivation of I_b from ICESat-2 data and its comparison with e.g. the ASAID product, I am surprised to see no comparison of the authors results with ASAID-derived H . At present this our best pan-ice sheet understanding of H , so it would be very useful to see a discussion of how your results compare here.

This is a very good advice. We have now compared the separations between ICESat-2-derived Point H and ASAID Point H in line 320-326, Table 2, Figs. 7b and 7d. The comparison shows an overall good agreement, the absolute mean separation and the standard deviation between the two products are 1.2 km and 0.98 km, respectively. 83% of the ICESat-2-derived Point H locate less than 2 km away from ASAID Point H which are within the geolocation error of ASAID Point H indicated by Bindenschadler et al. (2011).

Line 275 – As no reference is included to support this assertion, the discussion of crevasses and their influence of GZ reads like something of an afterthought, potentially degrading the reader's confidence in this otherwise highly impressive technique. Since this is predominantly a methods paper, I'd encourage the authors to elaborate on a) why they didn't (couldn't?) clean up these data, b) exactly how they think these phenomena may influence the overall accuracy of their technique and, if needed, c) briefly mention how future work may address this issue. I imagine a lot of this could (and should) go into Section 3 so that the reader can bear these uncertainties in mind while reading Section 4. In addition, it is generally poor grammatical form to begin new sentences with 'Also', 'However', 'It' etc., so the readers should consider revising the structure of the next sentence (and several other similar instances throughout the manuscript) to address these minor niggles.

Agree. We have now added a new section 3.1.4 'Filtering and visual validation' to explicitly explain how we filtered the wrong GZ identifications due to inaccurate error function fitting or data deficiency. We firstly applied quality check flags in our algorithm to filter the GZ results:

- i. Quality-0 : Potential good results passing the two quality checks below.
- ii. Quality-1 : data loss percentage flag. If the percentage of segments on the nominal reference track where there is no elevation measurement is larger than 50%, then it means this repeat-track data group does not have enough data to perform a reliable GZ calculation. This data deficiency can be caused by the cloud or snow.

- iii. Quality-2: inaccurate Error function fitting flag. Large across-track slope and crevasses can introduce significant amount of noise in MAEA curve and can result in an inaccurate Error function fitting when identifying GZ. If the distance between Point F and the reference GL exceeds 5 km, then the Error function fitting is possibly inaccurate.

However, there are several circumstances where quality flags are inaccurate in these three categories. For example, the existence of ice plain can result in up to 10 km separation between Point F and the reference GL, but the GZ results in this case are marked with 'Quality-2'. Also, large across-track slope can cause inaccurate GZ identification for single beam repeat-track data group (Figs. 6a-6d) in category 'Quality-0'. Therefore, we applied a final visual validation on all the GZ results with the aid of the flags to remove these wrong classifications.

Line 277 – Good point. Does the processing chain provide a means in which the user can obtain the number of repeat-track observations your GL picks are based on? Such information could be used to calculate a 'GZ pick reliability rating', and/or inform data users about the range of tidal frequencies the GZ is mapped over.

This is a very good advice. We agree that both the number of repeat cycles used in GZ calculation and the tidal amplitude range are very valuable information for analysing the reliability of ICESat-2-derived GZ features, studying the short-term GL migration, or separating the long-term GL retreat signal as another comment made by the reviewer:

Line 248 – “In addition, this also allows us to calculate the GZ features from just two time stamps of tidal amplitudes”. It’s obvious to me why the authors say this, but to some this might imply an element of inaccuracy in the author’s results. This is because recent research has shown that the GL can undergo significant changes in its position over a range of tidal frequencies, in some cases by as much as 4 km (e.g. Milillo et al., 2017, GRL). I suggest the authors acknowledge this important point, and mention that while their technique does indeed work using only 2 repeat cycle’s worth of data, the identification of longer-term GZ change completely distinct from tidal variability (e.g. Friedl et al. 2019) may only be possible as/when more ICESat-2 observations become available.

We have now included these two parameters in our automated workflow (line 187-189) and produced two figures (Figs. 7e and 7f) to show the number of repeat cycles and the mean tidal amplitude at each ICESat-2-derived GZ. We also discussed the uncertainties of GZ positions due to different ocean tidal amplitudes (line 297-300) and number of repeat cycles (line 329-336).

Specific Comments

Line 6 – While it’s beyond the scope of this review to provide detailed corrections to the style of English and grammar used throughout the manuscript, I’ve re-structured the abstract to greatly condense and more effectively convey the key selling points of paper here. The authors should feel free to amend/disregard as necessary. Authors should also note the omission of greater 'precision' relative to ICESat-1, as I strongly believe this is not convincingly addressed in the manuscript (see my comment above on line 190).

“We present a new, fully automated method of mapping the Antarctic Ice Sheet’s grounding zone using repeat-pass and cross-over analyses of newly acquired ICESat-2 laser altimeter data. Our method recovers the position of the landward limit of tidal flexure and the inshore limit of hydrostatic equilibrium, as demonstrated over the mountainous and hitherto difficult to survey grounding zone of Larsen C Ice Shelf. Since launching in 2018, our method has already doubled the number of grounding zone observations acquired from ICESat-1, which operated between 2003 and 2008. Acting as a reliable proxy for the grounding line, which cannot be directly imaged by satellites, our ICESat-2-

derived limit of tidal flexure locations agree well with independently constrained measurements, with a mean absolute separation and the standard deviation of 0.29 km and 0.31 km, respectively, from interferometric synthetic aperture radar-based observations. Our results demonstrate the efficiency, high spatial precision and density in which ICESat-2 can image complex grounding zones, and its clear potential for future pan-ice sheet grounding-zone mapping efforts."

Thanks for the comment. We have now modified the abstract based on the reviewer's suggestions and removed 'precision'.

Lines 18-21 – I think these opening sentences could be worded more eloquently to say something like: *"Long-term satellite observations have linked the on-going thinning of Antarctica's ice shelves (Paolo et al., 2015) to enhanced rates of ice mass discharge beyond the grounding line (hereafter GL) – the point where the grounded ice sheet first detaches from the bedrock and begins to float (Fricker & Padman, 2006). Ice discharge calculations are sensitive ..."*

Agree and amended.

Line 28 – Provide references for mass balance studies and those assessing overall ice sheet stability. The latest offering from the IMBIE crowd (Shepherd et al., *Nature*, 2018) would be good here.

Agree and amended.

Line 33 – Following my comment regarding Line 275, the authors should aim to avoid ambiguous terms like 'Its' to begin sentences. Suggest rewording to *"The precise width of the grounding zone depends on ..."*

Agree. This sentence has been modified and placed in line 338-339 *"The width of the GZ depends on ice stiffness, bed slope and ice thickness (Bindschadler et al., 2011), and is useful in determining the ice thickness and rheology across the grounding zone (Dawson and Bamber, 2020)."*

Lines 35-36 – This is a good example of many instances of repetition in the manuscript. The true GL (*G*) and limits of tidal flexure (*F*) have already been defined on line 30/31, so don't need to be repeated here. Saying something like the following would be much more concise and easier to understand.

"... While Point G cannot be detected directly from satellite-based observations, Point F resides within close proximity of this location, and is thus widely considered to be the most robust satellite-observable proxy for the "true" grounding line (insert references here)."

(Note that this rewrite also gets round the incorrect notion that the limit of tidal flexure is something only present on the ice sheet surface, when reality it is the surface manifestation of a variety of mechanical processes going on at the ice-bed-ocean interface)

Agree and amended (line 34-36).

I also suggest you replace any further mention of *"the true grounding line"*, *"the landward limit"*, *"limit of hydrostatic equilibrium"* etc. in the manuscript with 'Point G', 'Point F' and 'Point H'.

Agree and amended.

Also, in this instance 'Point' is a pronoun, and so should always be capitalized. (be sure to change this universally throughout the text and fig. captions).

Agree and amended.

Line 38 – Remove ‘to date’ (as it probably always will be ...).

Agree and amended.

Line 41 – Change to “Points F and H (Figure 1) have previously also been derived using ICESat-1 laser altimetry ...”

Agree and amended (line 41).

Line 43 – The use of the word ‘these’ is unneeded and can be removed.

Agree and amended.

Line 44 – Suggest replacing ‘data’ with “additional GZ information across regions ...”. Also hyphenate ‘DInSAR-derived’. For consistency with the above paragraph, please also refer to ‘DInSAR-derived GZ information’ rather than ‘GL information’ (since DInSAR recovers F, a *proxy* for G).

Agree and amended (line 43-44).

Line 46 – Change to “... In addition, ICESat-1-based GZ detection is heavily based on visual interpretation which requires a large amount of manual ...” for brevity.

Agree and amended (line 46-47).

Line 51 – Poor grammar. Suggest rewording and merging with the next sentence for clarity and conciseness. Something like: “ICESat-2 has a repeat-pass orbit time of 91 days, and – compared to the single Geoscience Laser Altimeter System (GLAS) onboard ICESat-1 – measures the surface elevation of Earth’s ice sheets using three photon-counting beam pairs emitted from the Advanced Topographic Laser Altimeter System (ATLAS)”.

Agree and amended (line 53-56).

Line 58 – Suggest shortening to: “... Point H by analyzing repeat-track and ascending/descending cross-over data. We chose the ...”. The following sentence is also very long and verbose, and should be condensed and/or split up for clarity.

Agree and amended.

Line 64 – Saying that you used 12 months of data (5 cycles) when in reality the bulk of your analyses only used 8 (3 cycles) is somewhat misleading, so I’d consider splitting this paragraph up into 2 parts. One part discussing the repeat track analyses (8 months of data), and a standalone, follow-up part discussing the cross-over analysis (extended dataset covering 12 months). At present there’s a lot of back-and-forth discussion between techniques, which took me several readings to fully understand what you meant.

Agree. We have now used the same period of data for both crossover analysis and repeat track analysis for consistency between the two methods (line 66-68) based on the comment by Reviewer 2.

Line 69 – For absolute clarity, do these RPT’s refer simply to the ‘Pair Track’ files included in the ATL06 products, or is this something you have calculated the position of? If the former, then I’d suggest just referring to them as ‘pair tracks’ (PTs) for consistency with ATL06 naming convention, and to avoid any possible confusion with the Reference Ground Track (RGT) information provided as part of the ICESat-2 orbit files (see: <https://icesat-2.gsfc.nasa.gov/science/specs>).

The original statement is inaccurate, ICESat-2 points at the Reference Ground Track (RGT). However, we also noticed the similar statement has been made in Page 7 of the ATL06 ATBD document (https://nsidc.org/sites/nsidc.org/files/technical-references/ICESat2_ATL06_ATBD_r003.pdf): “Note that in cycles 1 and 2 of the mission, ICESat-2 did not point at the RPTs, and ICESat2’s pairs are offset by up to 2 km from the RPT locations. The first cycle that was collected over the RPTs was the third”, which is confusing in terms of RGT and RPT.

To avoid any ambiguity, we have now modified the sentence into “The first two cycles of ICESat-2 data acquired between 14 October 2018 and 30 March 2019 are not repeat cycles because the spacecraft pointing control was not yet optimized” in line 65-66.

Line 83 – Should this say +/-15 m as opposed to 150 m? This value seems excessive, and I wonder how many values actually fell out with this range after your initial cleaning of the data?

We have removed this data filtering step according to the comment by Reviewer 2:

Lines 81 – 82: “In addition, the surface elevation was also compared with the reference DEM Reference Elevation Model of Antarctica (REMA) (Howat et al. 2019) provided in the ATL06 product...” This is extremely challenging in the region of the GZ. REMA elevations are not tide corrected; thus, their elevations in the GZ are time/scene dependent.

Lines 87-90 – Check grammar, punctuation and sentence tense. The first sentence is also repetitive and could easily be reworded to avoid double use of ‘repeat track’. Also, how/why does your cross-track slope correction ‘facilitate’ the automation of GZ mapping? Do you mean that it reduced the occurrence of incorrectly identified GZ features? I think a little more elaboration is needed here to explain this point. Sentence beginning line 90 should also be reworded to avoid the use of the word ‘it’.

Agree. We have now modified the sentence to “To identify the GZ features, we adopted a similar approach previously used with ICESat data by measuring the vertical motion of floating ice induced by ocean tides from a set of elevation anomalies for each repeat track (Brunt et al., 2010)”. Separate discussions on the advantage of across-track slope correction are now in line 106-118 and line 213-218.

Line 91 – Incorrect use of semi-colon and multiple unneeded uses of the word ‘the’. Also suggest changing ‘features estimation’ to ‘feature identification’.

Agree and amended in line 89-91: “The workflow of the repeat track analysis developed in this study includes four steps: 1) Repeat-track data preprocessing (section 3.1.1, box 1 in Fig. 3). 2) Elevation anomaly calculation (section 3.1.2, box 2 in Fig. 3). 3) GZ feature identification (section 3.1.3, box 3 in Fig. 3). 4) Filtering and visual validation (section 3.1.4).”

Paragraph beginning Line 93 – This is a good example of the ‘back-and-forth’ organization of the paper I mentioned in my general comments. That is, whereas reader expects this paragraph to involve a discussion of steps 1 and 2 detailed in line 91, the reader now has to go back to a discussion of repeat cycles and the grounding line reference product. In accordance with processing steps shown in Figure

3, I suggest the authors separate this part of the methods section into several distinct subheadings possibly labelled “3.1.1: Repeat-track data preprocessing” (to include discussion of nominal ref track calculation and search window size from reference GL dataset), “3.1.2: Cross-track slope correction” and “3.1.3: GZ component identification”. If the authors choose to do this, then each section should also be explicitly cross-referenced in line 91. The processing steps corresponding to each sub-section could also be indicated on Fig. 3 by enclosing each sub-section in a box.

Good advice. We have restructured the methodology section into the following subheadings and modified Fig.3 by enclosing each sub-section in a box:

- i. 3.1.1 Repeat-track data preprocessing (box 1 in Fig. 3).
- ii. 3.1.2 Elevation anomaly calculation (box 2 in Fig. 3).
- iii. 3.1.3 GZ feature identification (box 3 in Fig. 3).
- iv. 3.1.4 Filtering and visual validation.

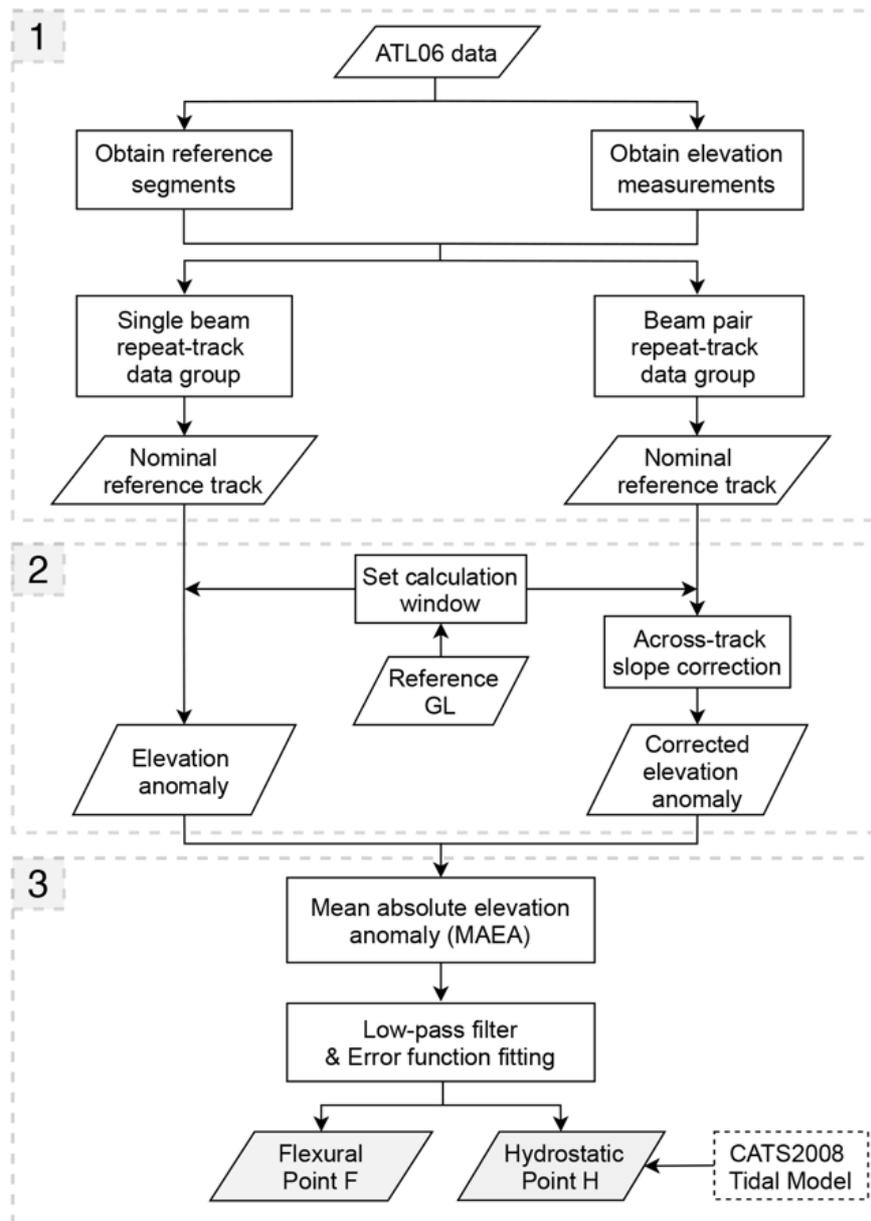


Figure 3. The ICESat-2 repeat-track workflow used to identify the grounding zone (GZ) in this study, including the limits of inland tidal flexure (Point F) and hydrostatic equilibrium (Point H).

Lines 93-96 – Be sure to emphasize here that you used all three beam pairs in your analyses, as readers may interpret from the current version of the text that only one beam was used.

Agree and amended. We have now emphasized in the methodology section that we generated single beam repeat-track data groups for all six different ground tracks (line 98-105), and beam pair repeat-track data groups for all three beam pairs (line 106-113). Also see Figs. 4a and 4b.

Line 99 – As per my comment on line 69. Should ‘RPT’ be ‘PT’? Also consider putting inverted commas around ‘nominal reference track’ to emphasize that this is a newly introduced term.

We have now removed ‘RPT’, and modified the statement to ‘we also derived the locations of every reference segment for each ground track from the segment_quality group of the ATL06 product’ (line 82-83) and ‘For each single beam repeat-track data group, a ‘nominal reference track’ (black circles in Fig. 4a) at an along-track interval of 20 m was calculated by averaging the locations of reference segments from all repeat tracks. The use of reference segments to obtain the nominal reference track can produce a common set of geolocation profiles free of the data loss of actual ground tracks.’ (line 102-105). We have put inverted commas around ‘nominal reference track’ in line 103.

Line 101 – Needed to do what? I suspect set a GZ detection search window size, but this isn’t obvious from the text.

We have changed the sentence into ‘Before calculating the elevation anomalies for each track inside the repeat-track data group, a reference GL estimate is needed to define a GZ search window in the calculation (Fig. 3 box 2)’ in line 120-121.

Line 103 – Why was the Mouginot dataset used over the ice rise information documented in Depoorter? Is it more accurate? More up-to-date? Explicitly state why you used this product here.

We have removed the Mouginot et al. (2017) grounding line product from the manuscript and used the Depoorter et al. (2013) grounding line for both the ice sheet and ice rises or ice rumples. As mentioned in the previous responses, we have now modified the reference GL by merging the latest ESA CCI DInSAR GL (2015-2016) with the Depoorter et al. (2013) GL to avoid the uncertainty of the GL location in the calculation (line 120-129).

Line 104 – What is an ‘initial GL product’? I see no mention of it in the text or Figure 3, and don’t know how it differs from the ‘reference GL product’ discussed in the same sentence.

The ‘initial GL product’ is the reference GL used in the algorithm. We have changed the sentence into ‘For each repeat-track data group, the reference GL was calculated as the intersection between the nominal reference track and the composite GL.’ in line 130-131 for clarity.

Line 111 – In 2017 Larsen C calved massive iceberg A-68 from its ice front, exposing an ~6000 km² area of previously ice-shelf covered ocean water. Mouginot’s coastline precedes this calving (and the ICESat-2 observational period), meaning that the authors have inadvertently included this huge section of open water in their analyses. This is clearly seen in Figure 2. I suggest the authors re-clip their dataset using a more up-to-date coastline, such as the one available at: <https://www.add.scar.org/>. The authors may also wish to consider clipping the velocity dataset shown in Figure 5 for consistency between figures.

Agree. We now use the SCAR Antarctic Digital Database (ADD) coastline to mask out the ATL06 data located in open water, please refer to line 136-138. All the related figures (Figs 2, 7, 10 and A1) have also been modified by using the ADD coastline mask.

Line 112 – This sentence is highly repetitive and includes ‘*elevation change*’ three times. Consider condensing.

We have now removed this sentence.

Line 119 – Insert comma after $h_{Li,G}$. Also, I presume here that ‘*Li*’ means linearly interpolated? Your choice of interpolation isn’t explicitly stated here, so if so, include that info here.

‘*Li*’ means land ice, for clarity we have now removed all the use of ‘*Li*’ in the equations (line 145-152).

Line 125 – “... are the *y* coordinates measured perpendicular to the RGT”. Can this be reworded to say “... are the across-track *y*-coordinates measured perpendicular to the RGT”? (I guess, after all, that this is what ‘*ATC*’ in e.g. ‘ $y_{ATC,x}$ ’ means?)

The reviewer is correct, we have amended the sentences in line 147-148 and line 152.

Also, following my comments on Line 69, the use of RGT here particularly qualifies the need to abbreviate ‘*Reference Pair Track (RPT)*’ to ‘*PT*’ in the text.

The use of RGT is correct here, please refer to the definition of y_{atc} provided in the ATL06 variable dictionary (https://nsidc.org/sites/nsidc.org/files/technical-references/ICESat2_ATL06_data_dict_v003.pdf): ‘Along-track *y* coordinate of the segment, relative to the RGT, measured along the perpendicular to the RGT, positive to the right of the RGT’.

Line 127 – Suggest changing “*in GZ estimation*” to “*used in our identification of the grounding zone*”. Remove unneeded period at the end of the last sentence.

Agree and amended in line 154.

Line 129 – Suggest changing to “*After applying the cross-slope track...*”. Also consider splitting this very long sentence in two between ‘*track*’ and ‘*which*’, and opening the new sentence with “*These profiles are shown in Figure 5a*”.

Agree and amended in line 154-156.

Also note here the irregular ordering of the Figures in text. Figures should generally be referenced in the text in alphabetical order, so in this instance I suggest swapping Figures 5a and b in Figure 5, and changing Line 131 to say ‘*5a*’. Same for line 132 (‘*5b*’). Also, remove “*color-coded dot curves*” here and in line 132; this is non-essential information best left for the caption.

Agree and amended.

Line 133 – Suggest: “*To estimate Points F and H from the elevation anomalies ... was calculated from the corrected ...*”

Agree and amended in line 162-163.

Lines 136-160 – Following my general comment, these paragraphs are very difficult to follow, as a) they flick back and forth between the identification of *F* and *H*, and b) it is highly unclear what ‘new’ identification procedures the authors have used versus that discussed in Fricker & Padman (2006). There is also a lot of repetition of content already mentioned in the introduction. I strongly suggest re-structuring these paragraphs to closely follow the structure outlined below:

First paragraph: Very brief overview of the anatomy of the GZ with respect to Points *F* and *H* and the work of Fricker & Padman (1-2 sentences). Then, a few sentences on how *they* identified the grounding zone.

Second paragraph: A discussion of how the authors expanded upon this earlier work and identified Point *F* using new slope-corrected techniques, MAEA and its second derivative. No mention of *H* here.

Third Paragraph: Discussion of how using MAEA alone is likely more difficult to identify Point *H*, and subsequently: how the authors used MAEA together with their error function to locate *H*. When discussing the error function, elaborate more on what “*as a guide*” means (readers should be able to replicate this method, so as written this seems vague/ambiguous).

Agree and we have modified the structure of the Section 3.1.3 ‘GZ feature identification’ based on the reviewer’s suggestion.

Line 163 – unneeded ‘*the*’ before elevation change. Also, this and next sentence are almost complete repetition, and should be condensed (and possibly merged with the following sentence). Also define ‘*KDTree*’ (and any other abbreviation) in full when using for the first time.

Agree and amended.

Sentence beginning line 168 – Poor grammatical structure.

Agree and amended.

Line 170 – Should this say ‘*from*’ instead of ‘*for*’?

Agree and amended.

Line 175 – Add Padman et al. citation after reference to the CATS2008a model. ‘*Movement*’ should be singular.

Agree and amended.

Line 178 – ‘*based on the results in section 4*’. What does this mean? State the explicit steps you took to derive this number here, and then refer to the results section, if still necessary.

The threshold for removing crossovers with the same tidal phase on ascending and descending track is defined based on the minimum tidal amplitude detected from the repeat track analysis, which can only be achieved by analysing all the calculated GZ results. We have now changed the statement into “As the minimum detectable tidal amplitude from repeat track analysis is 20 cm after analysing all the GZ features calculated in Section 3.1, we then set the minimum threshold of elevation change due to ocean tides on floating ice measured by the crossover analysis to be 40 cm by doubling the 20 cm threshold of repeat track analysis.” In line 240-243.

Sentence beginning line 180 – It is implicit in the above sentence that you did this, so suggest the removal of the sentence from the text.

We think it is necessary to keep this sentence. We only mentioned that the tidal amplitudes calculated from the CATS2008 Tidal Model were used as a reference for the vertical motion of floating ice but we didn't mention how we were going to use CATS2008 Tidal Model tidal amplitudes to filter the crossovers. This sentence provides important information on the method of filtering crossovers with the ascending and descending track in the same tidal phase.

Line 183 – suggest rewording to better match the structure of my suggested abstract changes. Suggest something like:

“Using our newly developed ICESat-2-based GZ detection algorithm, we recover a two-fold increase in the number of GZ features identified over Larsen C Ice Shelf by ICESat-1 (69 and 71 picks of Points F and H, respectively, versus 30 of each by ICESat-1). The spatial distribution of each platform’s GZ picks is shown in Figure 6, together with a comparison of Point F as determined from independent DInSAR observations. The improvement in our ability to image the GZ using ICESat-2 data is especially notable in heavily crevassed regions like Jason Peninsula and Churchill Peninsula (Jansen et al. 2010), which were previously difficult to image using single-beam ICESat-1 observations alone”.

Agree and amended in line 249-260.

Lines 189-195 – As per my technical comments on Lines 183-216. Suggest restructuring this paragraph and Figure 5 to only make reference the more up-to-date ESA CCI product.

Agree and amended in line 276-288.

Lines 189-201 – This paragraph is another example of the somewhat unorganized writing style discussed above, this time pertaining to the back-and-forth comparison of different sensor observations. Mirroring my suggested edits to the methods section regarding the derivation of *F* and *H*, I suggest re-structuring this and the following paragraph in the following order to greatly improve clarity.

First para: Discussion of how the author’s results compare with DInSAR observations (ESA CCI only). (Any comparison of ICESat-1 and -2 GZ points are largely unconvincing and should be excised from the text here).

Second para: Discussion of where your DInSAR and ICESat-2 *F* points don’t agree (i.e. the para beginning line 202. Nice findings, by the way!).

Third para: Discussion of how your *F* points compare with those imaged by other sensors, including CryoSat-2 (nb. A discussion of CryoSat-2 vs. ICESat-1/DInSAR observations is outwith the confines of this study, and as a predominantly ICESat-2 methods study, should be removed. Also note the incorrect spelling of *CryoSat-2*). In accordance with my earlier comments, I think this paragraph would also be the place to add in comparison of your *I_b* picks vs. those of the ASAIID product).

Fourth Para: Discussion of Point *H*, encompassing my comments on lines 233-235 above.

Agree and amended in Section 4.2 ‘Comparison with other GZ products’

Lines 206-210 – “(vertical red dash line)”, “(blue dash curve)” etc. is non-essential information best placed in the caption instead.

Agree and amended.

Lines 209-210 – Highly verbose sentence, and repetitive use of ‘left’ and ‘right’. This sentence should be condensed.

Agree and amended.

Line 220 – Insert comma before and after $|dh|$.

Agree and amended.

Line 221 – Change “the repeat track analysis” to “our repeat track analysis”

Agree and amended in line 308.

Line 223 – What does “same time difference” mean? Suggest rewording for clarity.

We have removed this example from the manuscript.

Line 224 – Suggest changing to “The locations of Point F identified using our repeat-pass technique (black dots in Figure 8c) are located in the middle of high and low $|dh|$ observations, indicating the presence of floating and grounded ice either side of Point F, respectively”.

We have removed this example from the manuscript.

Paragraph beginning line 227 – For simplicity and clarity, I would restructure this paragraph to first mention why we’re interested in knowing the width of the GZ, then discuss how it has been calculated in the past and then how the authors have calculated it in this paper. Then finish with a discussion of your results. Similar to the discussion of Points F and H within the context of independent observations, some brief words on how measured GZ widths compare with e.g. ASAIID GZ widths would also be well placed here. Also, the first sentence of this para is repeated directly from the introduction, so suggest rewording.

Agree. We have restructured and modified Section 4.3 ‘Grounding zone width’. Since ASAIID GZ was mapped between Points I and H but our method is based on the separation between Points F and H, we think it is inappropriate to compare our GZ width with ASAIID GZ width. Instead, we compared our results with the most recent CryoSat-2-derived GZ width on Larsen C Ice Shelf by Dawson and Bamber (2020), they measured Points F and H based on a similar method in detecting tidal flexure information.

Line 239 – Suggest changing to: “... for recovering several commonly imaged components of the ice-sheet-shelf grounding zone, including the inland limit of tidal flexure (Point F) and the limit of hydrostatic equilibrium (Point H). The new method presented in this study should ...”

We have removed this sentence from the manuscript.

Line 240 – “The new automated method presented in this study should allow a more efficient and consistent mapping of the Antarctic GZ features”. I see what the authors are trying to suggest here, but don’t think it’s articulated quite correctly. The authors should bear in mind that due to recent

advances in polar-orbiting EO capabilities (incl. the launch of Sentinel-1a/b), we can in theory now generate a precise understanding of the GZ every 6 days using DInSAR. The spatial-temporal coverage of e.g. DInSAR-derived F will therefore *always* be better than ICESat-2 F , so I think this sentence (and any similar arguments made further down in the discussion and conclusion sections) should be reworded to reflect this. What I think the authors want to say is that ICESat-2 provides an automated, efficient means of characterizing the Antarctic Ice Sheet's GZ, to complement the high-accuracy observations afforded by other modern Earth Observation sensors.

We have removed this sentence from the manuscript.

Line 241 – This sentence should go into more detail about why we are interested in GZ position change and width (e.g. for improving numerical models aiming to constrain SLR predictions, identifying Antarctica's most vulnerable regions to climate change etc.).

We have removed this sentence from the manuscript. The reasons why we are interested in GZ position change are in Section 1 'Introduction' (19-29).

Line 244 – Suggest rewording to *"To maximize repeat-track coverage over the GZ, our method considers the ground tracks of one ICESat-2 repeat cycle beam pair as two individual repeat tracks"*.

We have removed this sentence because we have now changed the ATL06 data used in this study and the repeat track analysis method, please refer to Sections 2 and 3.

Line 247 – Should say "... which was an issue when using ICESat-1 data to identify the GZ (Brunt et al, 2010) ...". *Estimation* implies imprecision, so *identify* or similar is better".

This sentence has been removed.

Line 248 – *"In addition, this also allows us to calculate the GZ features from just two time stamps of tidal amplitudes"*. It's obvious to me why the authors say this, but to some this might imply an element of inaccuracy in the author's results. This is because recent research has shown that the GL can undergo significant changes in its position over a range of tidal frequencies, in some cases by as much as 4 km (e.g. Milillo et al., 2017, *GRL*).

I suggest the authors acknowledge this important point, and mention that while their technique does indeed work using only 2 repeat cycle's worth of data, the identification of longer-term GZ change completely distinct from tidal variability (e.g. Friedl et al. 2019) may only be possible as/when more ICESat-2 observations become available.

Agree and amended in line 329-336, please also see our previous response to the reviewer's technical comment on line 277.

Line 240 – see my comments re: Line 240. While this was perhaps once true, with the launch of Sentinel-1a/b (and soon -1c) I think the authors should reword this to state how the two datasets will *complement* each other.

We have removed this sentence from the manuscript.

Paragraph beginning Line 257 – This paragraph is a bit 'matter-of-fact' or bullet-point-like, and at times not merited within the context of this paper (e.g. the review-like discussion of CS2 vs. ICESat-1 observations, which are independent of the method presented here). In any case, for simplicity I

would reword the paragraph to echo the structure the results section (see my comments on Lines 189-201), and again excise any discussion of ICESat-2 vs. ICESat-1 precision from the text. As this is the discussion section, a regurgitation of the exact separation distances is also not essential here. Also, to avoid any possible confusion, I would refrain from referring to 'GL detection' when referring to non-Point G components of the GZ.

Agree and amended in Section 4.2.

Line 264 – “ice plains that are difficult to capture from DInSAR ...”. Careful! Sentinel-1 DInSAR can capture it just fine (see below), so I'd reword this.

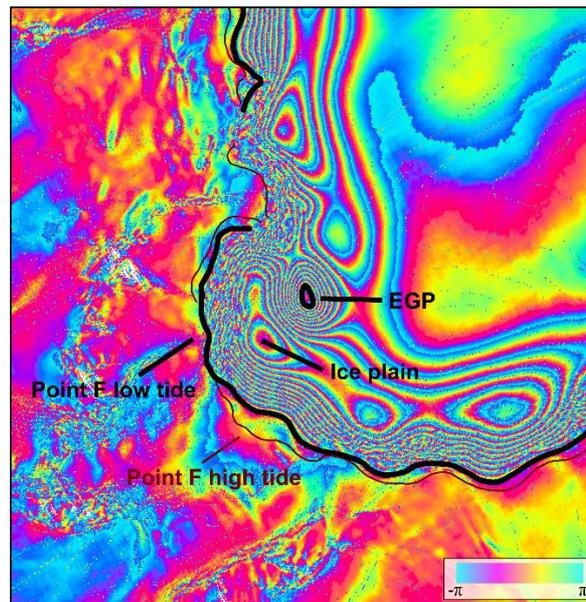


Figure 1 – Churchill Peninsula ice plain detected from double-difference InSAR applied to 2019 Sentinel-1a/b data.

Agree, this statement has now been removed.

Line 268 – “..., it demonstrates”. What demonstrates?

We have now changed this sentence into “In addition, proving our method works at a 20 cm scale tidal amplitude in a region with complex relief demonstrates the ability for the generation of GLs for the majority of the Antarctic Ice sheet” in line 300-312.

Lines 270/271 – Where are these tidal estimates derived from? CATS2008a? Cite the appropriate reference here. Also, remove the space separating this and the next paragraph.

They are from CATS2008 Tidal Model, we have now added the citation in line 304.

Lines 279 – Suggest rewording to something more concise like “Surface elevation changes derived from ICESat-2 cross-over data also provide valuable information about the approximate location of Antarctic grounding zones”.

Agree and amended in line 314-315.

Line 281 – should say “... separation afforded by repeat track observations, it can still reveal the approximate location of the GZ”. I also suggest the next sentence reads: “In doing so, this method has the potential to provide important validation of repeat-track-derived GZ features, including along fast-flowing ice streams where the GZ often undergoes rapid changes ...” or similar.

Agree and amended in line 315-317.

Line 283 – Restructure sentence to condense and avoid the use of ‘Also...’. This and the next sentence could also be easily merged.

Agree and amended in line 317.

Line 288 – This sentence is rather verbose, and I think it could easily be shortened and/or restructured to convey the key selling point of paper more effectively (see my wording of the abstract above).

Agree and amended.

Sentence beginning Line 288 – ‘the 8-month period’.

Agree and amended, now is the 10-month period of data.

Sentence beginning Line 293 – Larsen C Ice Shelf is a pronoun and so the preceding use of the word ‘the’ is incorrect and should be removed. Next sentence once again begins with ‘it’. What does ‘it’ refer to? Reword for clarity.

Agree and amended.

Sentences beginning Line 294 – I would let the readers decide if the separation between your ICESat-2 and DInSAR observation are small, so remove ‘small’ here. Also change all instances of ‘GL’ to ‘GZ’ for accuracy, and hyphenate all uses of the word “derived”.

Agree and amended.

Line 296 – Again, I'm just not sure you can confidently talk about ICESat-2 vs. ICESat-1 precision that way. Also, as far as I can tell, in the current version of the manuscript the authors make no direct comparison between their ICESat-2- and any CryoSat-2-derived *F* products, so don't think any robust statements can be made regarding precision in that sense either. As a result, I think this sentence should be restructured to echo my suggested restructuring of the results section.

Agree and we have removed this sentence.

Line 297 – Change ‘this method’ to ‘our method’ and remove ‘the’ before Larsen C Ice Shelf.

Agree and amended in line 364.

Line 298 – Insert a comma after ‘range’.

Agree and amended in line 365.

Line 299 – rephrase to avoid “it still shows”. Also ‘GL’ should say ‘GZ’.

Agree and amended.

Line 301 – Suggest changing to “...Antarctic Ice Sheet, similar cross-over-based analyses have the potential to provide more accurate depictions of the GZ”.

Agree and amended in line 370-371.

Sentence beginning line 301 – This is almost complete repetition of lines 293-295, so I suggest removing it from the text.

Agree and removed.

Line 310 – Where can the ESA CCI DInSAR data be found?

We have now added ‘We thank the European Space Agency (ESA) for providing the ESA CCI DInSAR grounding line data’ in line 378-379.

Line 333 – Incorrect dataset cited.

Agree and amended.

Figure 1 – It may just be the way the PDF has rendered the image, but as printed, the vertical lines pointing to each of the GZ components have different line thicknesses and slightly different colors. Suggest the authors standardize all thicknesses and colors if this is not a rendering issue.

We have now standardized all the thickness and colors of the plot.

Figure 1 caption – Capitalize all instances of ‘Point’.

Agree and amended.

Figure 2 – As previously discussed, suggest the authors clip their dataset to the modern-day coastline (i.e., account for A-68’s calving where elevation clearly equals zero over open water in the fig) and only show the 2017 (ESA CCI) grounding line. I also wonder if the authors inadvertently clipped Bawden Ice Rise out of their analyses? Like Gipps Ice Rise, this is an important pinning point for Larsen C (c.f. Borstad et al., 2017; *GRL*), so it’d be interesting to see any available GZ picks here. I suggest also standardizing the font size of all labels on the main map, and instead assigning track labels a different font color to better contrast against place-names. I also suggest center justifying the scale bar relative to the other items of the legend, and moving all items slightly to the left (at the moment the 1000 m label intercepts the figure border and looks untidy). Taking potentially color-blind readers into consideration, I’d also encourage the authors to choose another, non-jet/rainbow color ramp.

We have now clipped the datasets using the ADD coastline mask, changed font size and colors of the labels, adjusted the legend and changed the colorbar. We used the Depoorter et al. (2013) GL in the background to show the complete GL coverage in this region especially for Bawden and Gipps Ice Rise and Hearst Island where ESA CCI grounding line is not available.

Figure 2 caption – Capitalize ‘Ice Shelf’ and amend caption to reflect the addition of the 2017 (ESA CCI) grounding line. Remove ‘in Antarctica’ as the inset clearly shows this. As the grid is shown in meters, please also state the coordinate reference system used (e.g. EPSG:3031 Antarctic Polar Stereographic) (same for Figs. 6 and 8).

Agree and amended.

Figure 3 – As per my comments on the paragraph beginning Line 93, authors might consider enclosing the various sub-sections of their methodology with boxes. ‘Nominal Reference Track’ and ‘Hydrostatic Point H’ should also be shifted so as to not impinge on the boxes. Capitalize ‘Point F’ and ‘Point H’.

Agree and amended.

Figure 3 caption – Suggest “The ICESat-2 repeat-track workflow used to identify the grounding zone (GZ) in this study, including the limits of inland tidal flexure (Point F) and hydrostatic equilibrium (Point H)” (note: In general, abbreviations should be written in full in figure captions, which is why I have done so here).

Agree and amended.

Figure 4 caption – Suggest either amending the figure or stressing in the caption that this image only refers to 1 of the 3 beam pairs imaged by ICESat-2 at any one time (not all readers will be familiar with the 3-beam imaging capabilities of ICESat-2).

Agree and amended.

Figure 5 – Why is repeat cycle 5 not shown? In the main text it is stated that this dataset is used, so its omission here is rather odd. Suggest also ordering the repeat cycle legend in numerical order (3l, 3r, 4l, 4r and so on). Also, I don’t quite understand the inclusion of elevation by latitude (dashed profiles) here? The only reason I can think of is because track 1192 overpasses two GZs on the north and south of the unnamed ice rise seen in Fig.2 (and so should have some easily identifiable break-in-slope), but even then it’s unclear where this happens. In any case, when superimposed over the anomalies and other info it makes for a rather busy diagram, so I’d suggest removing it for simplicity. If the authors feel this is essential information, then I recommend they include it either as an additional sub-panel to this figure (cf. Fricker et al., 2006) or as a supplement.

In all panels, some of the axis and other labels appear cut-off, so care should be taken to fix these minor blips.

We have now included all the repeat cycles (3, 4, 5 and 6) used in this study and reordered the repeat cycle legend in numerical order. We changed the figure into a similar layout as Fig.3 in Fricker and Padman (2006) to improve the overall clarity.

Figure 5 caption – This is a very long and difficult to comprehend sentence (and caption overall). Can it be condensed somehow? I’m also not sure the second sentence makes grammatical sense, and could be shortened to: “in the legend, c03_1r refers to the right ground track of ICESat-2 pair 1, repeat pass 3”. After the Padman reference, insert “following Fricker & Padman, 2006”. Information about the derivation of MAEA has already been discussed in the text, and so should not be included in the caption. Capitalize all instances of the word ‘Point’.

Agree and amended.

Figure 6 – Same comments as Figure 2 regarding the center justification and movement of the items in each of the legends. Authors may also wish to consider clipping the velocity map for consistency with Fig. 2. Update DInSAR coverage to only show the 2017 Point F. In c what do boxes A and B refer to? (This isn’t stated in the caption). I think they refer to the spatial extent of Figs. 8a/b - if so, suggest

labelling 'Fig. 8a' and 'Fig. 8b' here, and similarly indicating the extent of Fig. 8c. Also standardize the thickness of the DInSAR Point F line in all plots.

Agree and amended, this figure is now Fig. 7.

Figure 6 caption – Once again, 'estimates' inherently suggests imprecision, so suggest rewriting caption to begin: "ICESat-2-derived inland limits of tidal flexure (Point F; red dots). For comparison, ICESat-1-derived Point F (Brunt et al., 2010) picks are also shown (blue dots), and data are superimposed over on recent ice surface velocity magnitudes (Rignot et al., 2017). b) same as a), but showing ...". Then, at the end, "in all plots, DInSAR derived Point F is also shown".

Agree and amended.

Figure 7 – As per my comments on Fig 5. Also, is there any way to re-size the labels in c and d so that they don't cross over the reference lines and data? At present these look messy.

Agree and amended, this figure is now Fig. 8.

Figure 7 caption – Another long and verbose caption which, being very similar to the caption of Figure 5, can be easily shortened to "Same as Figure 5, but showing ...".

Agree and amended.

Figure 8 – In all subplots, show only the 2017 ESA CCI Point F lines. In c, a black circle appears to be obscuring a blue circle. Suggest using unfilled black circles (i.e. outline only) in all subplots to avoid this. Suggest also scaling the black circle in the legend to match the its size as shown in the sub plots.

Agree and amended, this figure is now Fig.9. We have now changed this figure to only include the crossovers on Hearst Island, we kept using the filled black circles because the current figure doesn't have the same overlaying issues as the previous submission.

Figure 8 caption – Incorrect grammar. Suggest "Spatial distribution of ICESat-2 crossovers analyzed in this study. The spatial extent of plots a-c is shown in Figure 6c. At each location, the absolute change in elevation, $|dh|$, is shown. Background is ...".

Agree and amended.

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Reviewer 2

Mapping the Antarctic Grounding Zone from ICESat-2 Laser Altimetry Tian Li, Geoffrey J. Dawson, Stephen J. Chuter, Jonathan L. Bamber

This paper uses ICESat-2 data to identify the grounding zone of the Larsen C Ice Shelf, Antarctica. It builds off of methods developed for ICESat and automates some of these processes. The authors describe a modified repeat-track analysis (that uses 6.5 months of ICESat-2 data) and a crossover analysis (that uses 1 year of data) to determine a GZ that is in close proximity to the continuous GL assessment from the DInSAR GL of Rignot et al., 2016; this agreement is heavily based on the increased resolution of the ICESat-2 data, and not a measure of precision, as the authors contest.

The paper overall needs a fair bit of rewriting, with some text being repetitive and other sections feeling out of place. More care needs to be taken with respect to using uniform language with respect to terms that are introduced. And more care needs to be taken with respect to references ('et al.' is often, but not always, missing).

The method presented here builds off of methods developed for ICESat (please change all references of 'ICESat-1' to 'ICESat'). Some of the modifications may be relevant (such as the across-track slope correction) but are not strongly justified; other changes (or additions) do not seem to add to the results on this ice shelf (such as the crossover analysis).

Thanks for the comments, please see the major changes we have made in light of the comments by both the reviewers in our response to Reviewer 1.

My major comments include:

1) Why do the authors utilize a across-track slope correction and migrate the analysis to the 'nominal reference track'? In line 97, the authors state that the ICESat-2 "separation between same side ground tracks in a pair from different repeat cycles is less than 10 m". I do not expect substantial across-track slope, or rough terrain, at 10-m length scales. Uncorrected elevations in Figures 5a and 5b confirm this. The authors could instead produce repeat-track assessments through the GZ for all 6 ground tracks, increasing the number of point F and point H assessments substantially. If the across-track slope correction is needed for more subtle reasons, the authors need to better justify this.

This is a very good point. At the time when we developed this method, there wasn't a sufficient number of repeat cycles, so we treated the two beams in a beam pair as two individual 'repeat tracks' to maximise the data we could use, as using a small number of repeat cycles (i.e. 2) on individual beams resulted in noisier data especially in high-sloping regions. With the addition of more cycles, we have now been able to include the repeat track analysis for individual beams (Section 3) in our study. However, in some high-sloping areas such as the case for the left beam in track 506 beam pair 2 (Figs. 6a-6d), it is clear that a ~10 m separation cannot solve large across-track slope and resulted in a wrong GZ identification, but the across-track slope correction can greatly reduce this error (Figs. 6e-6h). In addition, the high elevation anomalies around the coupling point shown in Figs. 8b and 8c also show that the across-track slope can be significant over a 10-m scale.

Therefore, we think it is important to keep the across-track slope correction for beam pair in our methodology for high-sloping regions, at the same time we also performed the analysis for single beam repeat tracks to increase the density of GZ observations. The modified methodology is in Section 3, the discussion of the GZ identification by these two methods is in line 261-272.

2) I do not believe that the crossover analysis provides any additional merit to the existing repeat-track analysis for the Larsen C. As the authors mention, it might be more useful in more southerly ice shelves. I suggest removing that element from the paper and using it at a later date.

We have now used the latest version 3 ATL06 data for crossover analysis. We also added an additional step - 'For crossovers calculated from different cycles at the same location, we also averaged the elevation differences at each crossover location' (line 245-246), this removes a lot of noise observed in the previous data. The distribution of crossovers $|dh|$ on Hearst Island (Fig. 9) shows a clear transition from land ice (low $|dh|$) to floating ice (high $|dh|$), which aligns well with repeat-track-derived Point F and the REMA break-in-slope. Although the spatial separation between crossovers is much larger than the 20 m along-track separation afforded by repeat track analysis, this example still demonstrates how crossover analysis can be used to validate the repeat-track-derived GZ feature, and shows the potential for the application of this method to southern regions of the Antarctic Ice Sheet.

3) The authors state that the agreement between this GZ and the GL of DInSAR is an indicator of increased precision, relative to ICESat; 'precision' is not a great term for this. The close agreement is undoubtedly due to the increased across-track and along-track data density associated with ICESat-2; this is a spatial resolution improvement, not a 'precision' improvement.

We agree that the close agreement between ICESat-2-derived GZ and ESA CCI DInSAR GZ observations are benefited from the increased across-track and along-track density of ICESat-2 data. We have now removed the word 'precision'.

Specific comments:

Throughout: 'ICESat', not 'ICESat-1'

Agree and amended.

Throughout: Clean up the references (missing 'et al.' often)

Agree and amended.

Title: this is a bit misleading, suggesting that this is a result for the entire Antarctic. The definite article is not appropriate here. I suggest somehow adding 'Larsen C' to the title.

Agree and we have changed the title into 'Mapping the Grounding Zone of Larsen C Ice Shelf, Antarctica, from ICESat-2 Laser Altimetry'.

Line 10: the results *should* show a three-fold increase; why only 2?

Using the modified repeat track analysis method in Section 3, our results now show a near nine-fold increase in ICESat-2-derived GZ features compared with ICESat, this agrees well with the nine sets of repeat-track data groups generated in our repeat track analysis workflow.

Line 30: Point I is poorly characterized in Fig 1 and not mentioned in this paragraph. Suggest removing it from figure.

We have now modified Fig. 1 to better characterize Point I and included the relevant explanation on Point I in line 33 and line 48-50.

Lines 49 – 51: “The launch of ICESat-2 on 15 September 2018, as a successor to the ICESat-1 satellite mission, can achieve higher along track spatial resolution as well as nine times better coverage compared with its predecessor, providing the potential to map the GZ with greater accuracy and spatio-temporal coverage.” This needs to be better described. There are both along-track and across-track data density issues here. And there are more repeats within a calendar year. But that’s not captured explicitly in this text.

Agree and amended in line 65-72.

Lines 64 – 68: The time span is unnecessarily complicated in this section. A couple options: 1) remove the crossover analysis. 2) reduce the time span of the crossover analysis to match the repeat-track analysis.

Agree and we have now used the same period of data for both crossover and repeat track analyses (line 65-72).

Lines 67 – 68: Note that ICESat-2 was not operational for much of July. And the analysis stops halfway through November. Thus, there are really only 6.5 months of repeat track analysis, and cycle 4 (?) is not a complete cycle.

Agree and amended in line 66-70.

Line 69: “... ICESat-2 did not point at the Reference Pair Track (RPT)” Careful here; ICESat-2 points at the RGT; the RPTs are specific to the ATL06 data product.

We agree with the reviewer that ICESat-2 points at RGT based on the definition of RGT from the ATL06 ATBD (https://nsidc.org/sites/nsidc.org/files/technical-references/ICESat2_ATL06_ATBD_r003.pdf): ‘The reference ground track (RGT) is the track on the earth at which a specified unit vector within the observatory is pointed’. However, we have noticed the similar statement on RPT was made in Page 7 of the ATBD “Note that in cycles 1 and 2 of the mission, ICESat-2 did not point at the RPTs, and ICESat2’s pairs are offset by up to 2 km from the RPT locations. The first cycle that was collected over the RPTs was the third”. To avoid any ambiguity, we have now modified the sentence into “The first two cycles of ICESat-2 data acquired between 14 October 2018 and 30 March 2019 are not repeat cycles because the spacecraft pointing control was not yet optimized” in line 65-66.

Line 73: The start of this paragraph could be smoother; something like, ICESat data were corrected for ocean tides and had to be retided; ICESat-2 ATL06 data are not...

Agree and amended in line 74-76.

Lines 81 – 82: “In addition, the surface elevation was also compared with the reference DEM Reference Elevation Model of Antarctica (REMA) (Howat et al. 2019) provided in the ATL06 product...” This is extremely challenging in the region of the GZ. REMA elevations are not tide corrected; thus, their elevations in the GZ are time/scene dependent.

Agree and we have now removed this data filtering step.

Line 83: “elevation differences with REMA fell outside a ± 150 m threshold” What? 150 m of elevation differences?

We have now removed this data filtering step.

Line 108: “300 m were removed as the surface elevation of GZ” How many points did this remove? Were many of these points picked up by the ATL06 quality summary?

We set the 300 m threshold to remove ATL06 elevations located on land ice that are not needed in the GZ calculation, this improved speed of the analysis (line 134-136). As this is not a quality filtering for the ATL06 data, it is inappropriate to compare with the ATL06 quality summary flag.

Line 112: “The elevation change calculated from repeat tracks is a combination of cross-track slope induced elevation change ...” You say above that the repeatability is 10 m; I do not think that there is appreciable slope on 10-m length scales. I think what you are trying to say is that 1) you are prescribing height changes to the Nominal Reference Track (language from figure) or the RPT (language from above); 2) slope on 90 m length scales are important. Suggest 2 things here: 1) get the language between figure 4 and the text above more common; and 2) state from the onset that your analysis is being done on the RPT. Although, as I stated above, I do not think a slope correction is needed with 10 m repeatability.

Please refer to our response to the first major comment. We have now explicitly explained in the manuscript that the calculation was performed along the nominal reference track for each repeat-track data group, which is the average of all reference segments of each track (Section 3.1.1).

Lines 113 – 114: “As only 8 months of repeat cycles from March to November 2019 were used, ...” As stated above, it’s really only 6.5 months with the loss of July.

Agree, the current study period is actually 10 months.

Line 121: Define these terms before equation 2 is introduced. Spell out h_{LI} is (I assume) height for ‘land ice’; but what is y_{ATC} ? What does ATC stand for?

Agree and amended, please see our response to Reviewer 1.

Line 125: RGT? Or the actual surveyed ground track?

The use of RGT is correct here, please refer to the definition of y_{atc} provided in the ATL06 variable dictionary (https://nsidc.org/sites/nsidc.org/files/technical-references/ICESat2_ATL06_data_dict_v003.pdf): ‘Along-track y coordinate of the segment, relative to the RGT, measured along the perpendicular to the RGT, positive to the right of the RGT’. Please also see our response to the comment by Reviewer 1.

Line 126: Nominal? Or calculated mid-point for the actual surveyed ground tracks?

Here we use the nominal reference track, which was calculated by averaging all the reference segments for each ground track stored in ‘segment_quality’ group of ATL06 data (line 82-84 and 102-104). The reason of using reference segments to calculate nominal reference track is to produce a common set of geolocation profiles free of the data loss of actual surveyed ground tracks.

Line 126: “The average of all cross-track slope corrected elevations...” I’d be clearer and uniform with language. For clarity, start with ‘elevations’ (that’s what they are) and then use a single term throughout (e.g., the start of the next paragraph); I’d call these ‘elevations corrected for cross-track slope’.

Agree and amended.

Line 129: “After the cross-track slope correction for each ground track in a pair, ...” This is not clear.

Agree and amended in line 154-156.

Line 130: ‘reference elevation profile ...’ Use uniform language when defining terms; make this match the language from the last paragraph.

Agree and amended.

Lines 131–132: Watch the order of how you introduce Figures.

Agree and amended.

Line 141: “consistent with the local tidal amplitude...” Cite the source of that amplitude.

Agree and amended.

Line 152: This paragraph needs a rewrite; it’s overall confusing

Agree and amended (Section 3.1.3), please see our response to Reviewer 1.

Line 158: “predictions at 10 km offshore...” 10 km may be too large to extend the methods to complex GZs; suggest 1 km.

We have changed this value to 5 km (line 184-186). We don’t think 1 km is an appropriate choice here as the average GZ width is typically around 5 km, $\sim 3.2 \pm 2.6$ km for Ross Ice Shelf (Brunt et al., 2010) and $\sim 5.2 \pm 2.7$ km for Filchner-Ronne Ice Shelf (Brunt et al., 2011). Ice shelf at 1 km offshore from the reference GL may not be in full hydrostatic equilibrium for most of the regions.

Line 163: The sentence starting on this line is confusing. I think the authors are using the KDTree to get data in proximity to crossover points, and then finding the absolute location using the quadratic functions? This needs to be cleaner/clearer.

The reviewer is correct, we have modified the description in Section 3.2.

Line 164: Wrote out and partially describe KDTrees.

Agree and amended.

Line 168: What is ‘THE valid elevation measurements’?

We have now removed the word ‘valid’ for clarity.

Line 173: “where the elevation exceeded 20 m”: It’s totally fair to have a cutoff; but suggesting that 20 m is a temporal (accumulation?) change is not the right justification.

We have now changed this threshold to 10 m and changed the sentence into ‘we deleted the crossovers where the elevation difference exceeded 10 m to remove other errors such as the geolocation errors of ICESat-2 (Smith et al., 2020)’ (line 235-236).

Line 175: cite CATS.

Agree and amended.

Line 177: The sentence starting on this line isn't clear to me; I think you used a 40 cm offset for the crossovers based on 20 cm offsets from the repeat-track analysis. But it needs to be cleaner/clearer.

The reviewer is correct, we have now modified the relevant description in line 240-243, please also see our response to Reviewer 1.

Lines 184 – 191: Every reference in this section is missing an 'et al.'; this is common throughout. I'm not looking for all of them.

Agree and amended.

Line 192: "ESA CCI DInSAR GL (ESA Antarctic Ice Sheet Climate Change Initiative, 2017)" Delete the abbreviation part of this.

Amended.

Line 192: How is 'separation' defined? Absolute distance? Distance along the ground tracks?

It was measured as the perpendicular distance from ICESat-2 Point F to DInSAR Point F line segment (line 277-278).

Line 199: For the sentence that starts here, this really isn't a validation; these results just suggest that the point H identified using the repeat-track method is actually on the fully hydrostatic part of the ice shelf; but it doesn't validate that it's the first point of hydrostatic equilibrium, or point H.

We have now removed this sentence.

Lines 206 – 209: I am not sure what this is saying.

We have now removed this section and reexplained the ice plain based on the repeat track analysis for the right beam in track 506 beam pair 1 (Fig. 8), relevant discussion is in line 289-304.

Lines 206 – 216: I do not follow the line of thought here and therefore am not convinced that this rationale and Figure 7 suggest an ice plain.

This is an ice plain based on the example shown in Fig. 8, the detailed explanation is in line 289-304.

Line 215: 'Coupling Line' is not fully defined; the authors should also cite Hugh Corr's work on Pine Island Glacier.

Agree and amended.

Line 219: "... crossover analysis can provide additional information on the GL location." I don't think that this is true for Larsen C; there isn't the spatial resolution for this to add (or validate) the locations of points F and H. I suggest saving this method (crossover analysis) for a later paper, where the method is more appropriate.

We have now modified the data and the method used in crossover analysis, and updated the distribution of crossovers $|dh|$ on Hearst Island shown in Fig. 9, please also see our response to the second major comment. We think the current results can demonstrate the merit of crossover analysis.

Lines 225 – 226: I do not think that this method provides a validation. What about the pink point above the black F in 8c?

Please see our previous responses.

Line 231: “By assuming that the reference GL used in section 3.1 ...” Cite Depoorter again to remind people what you are referring to.

We have now updated the reference GL used in repeat track analysis by merging the 2015-2016 ESA CCI DInSAR Point F and the Depoorter et al. (2013) GL (Section 3.1.2). Please also see our responses to Reviewer 1.

Line 234: ‘9.73 km’: Why such a large outlier?

The current results show the largest GZ width is 11.62 km which locates inside a concave inlet of a glacier in Churchill Peninsula (Fig. 10). This GZ width could be associated with ice thickness and the geometry of GL in this region, but a detailed investigation of the underlying reasons exceeds the research scope of this study (line 345-351).

Lines 238 – 240: “The aim of this study is to assess the capability and the accuracy of ICESat-2 laser altimetry data for estimating the GZ features of the Antarctic Ice Sheet including flexural point F and hydrostatic point H.” I'd remove this; it doesn't offer anything new. But the next sentence does.

Agree and amended.

Lines 244 – 245: “... the new method takes two ground tracks of one beam pair from one repeat cycle as two repeat tracks.” I do not understand this sentence.

We have now removed this sentence.

Lines 253 – 254: “...ICESat-1 repeat track analysis which required multiple repeat tracks (normally from at least five repeat cycles) with large temporal differences (Brunt et al. 2010; Brunt et al. 2011).” This statement is not accurate and was not a result in the references provided. There are figures in those papers that use fewer repeats.

Agree and amended. Discussion on the advantage of the capability of our method in identifying GZ based on only two repeat cycles is in line 329-336, please also see our responses to Reviewer 1.

Line 258: (and throughout) As noted in my initial comments, ‘precision’ is not a great term for this. The close agreement is undoubtedly due to the increased across-track and along-track data density associated with ICESat-2; this is a spatial resolution improvement, not a precision improvement.

We have now removed the word ‘precision’, please also refer to our response to the third major comment.

Line 267: ‘and’; the 2 clauses on either side of this have nothing to do with one another.

Agree and we have modified this sentence into 'proving our method works at a 20 cm scale tidal amplitude in a region with complex relief demonstrates the ability for the generation of GLs for the majority of the Antarctic Ice sheet' in line 300-302.

Line 272: The results in this paragraph are a direct repeat of the results from Fricker & Padman 2006, and Brunt et al., 2010, 2011. The authors need to present how they have added to these results.

Agree and amended. We have included a new section 3.1.4 'Filtering and visual validation' to explain how we filtered the wrong GZ identifications due to inaccurate Error function fitting or data deficiency. Please see our detailed response to Reviewer 1.

Lines 279 – 280: "provide valuable information about the position of GL in the Antarctic Ice Sheet." I don't think this is accurate. I don't see what these assessments add, with respect to location of the GZ.

Please see our previous responses to the review comments on crossover analysis.

Line 281: "it still can show the general location of the GL" I just don't see this.

Please see our previous responses to the review comments on crossover analysis.

Figure 1: Consider removing point I or including it in the text with detail. From the figure, it is hard to discern if this is capturing I_m or I_b.

We have now modified Fig.1 to better characterize Point I and included the relevant explanation on Point I in line 33-34 and 48-50. Please also see our previous responses.

Figure 4b: I would not repeat the color scheme of 4a; this suggests that different cycles are required for this method.

Agree and amended.

Figure 5: Trim the caption. For the legend next to 5b: why are they ordered like this? Why are the purple and olive lines not included? What are the purple and olive lines?? I think they are elevations. It looks like there are 4 lines there (blue and orange??). That is confusing.

Agree and amended.

Figure 7: Trim the caption. Some of the language (e.g., defining MAEA again) is repetitive and can be removed. Overall, this figure is confusing and does not convince me that this is an ice plain. Figure 7d is especially confusing.

Agree and amended.

Figure 8: 8b shows that the spatial resolution of these crossovers does not add to the results associated with the repeat-track analysis. Suggest removing this.

We have changed this figure into Fig.9 and only showed the distribution of crossovers $|dh|$ on Hearst Island where the ESA CCI DInSAR Point F is not available. The new results can show the approximate location of grounding line, thus we think it's important to keep the crossover analysis in this study. Please also see our previous responses on crossover analysis.

References cited in authors' response:

Bindschadler, R., Choi, H., Wichlacz, A., Bingham, R., Bohlander, J., Brunt, K., Corr, H., Drews, R., Fricker, H., and Hall, M.: Getting around Antarctica: new high-resolution mappings of the grounded and freely-floating boundaries of the Antarctic ice sheet created for the International Polar Year, *The Cryosphere*, 2011.

Brunt, K. M., Fricker, H. A., Padman, L., Scambos, T. A., and O'Neel, S.: Mapping the grounding zone of the Ross Ice Shelf, Antarctica, using ICESat laser altimetry, *Annals of Glaciology*, 51, 71-79, 2010.

Brunt, K. M., Fricker, H. A., and Padman, L.: Analysis of ice plains of the Filchner–Ronne Ice Shelf, Antarctica, using ICESat laser altimetry, *Journal of Glaciology*, 57, 965-975, 2011.

Dawson, G. J., and Bamber, J. L.: Measuring the location and width of the Antarctic grounding zone using CryoSat-2, *The Cryosphere*, 14, 2071-2086, 2020.

Depoorter, M. A., Bamber, J., Griggs, J., Lenaerts, J., Ligtenberg, S. R., Van den Broeke, M., and Moholdt, G.: Calving fluxes and basal melt rates of Antarctic ice shelves, *Nature*, 502, 89, 2013.

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Fricker, H. A., and Padman, L.: Ice shelf grounding zone structure from ICESat laser altimetry, *Geophysical Research Letters*, 33, 2006.

Mouginot, J., B. Scheuchl, and E. Rignot: MEaSURES Antarctic Boundaries for IPY 2007-2009 from Satellite Radar, Version 2, <https://doi.org/10.5067/AXE4121732AD>, 2017.

Rignot, E., Mouginot, J., and Scheuchl, B.: MEaSURES Antarctic Grounding Line from Differential Satellite Radar Interferometry, Version 2, <https://doi.org/10.5067/IKBWW4RYHF1Q>, 2016.

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Mapping the Grounding Zone of Larsen C Ice Shelf, Antarctica, ~~Antarctic Grounding Zone~~ from ICESat-2 Laser Altimetry

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Abstract. We present a new, fully automated method of mapping the Antarctic Ice Sheet's grounding zone using a repeat track analysis and crossover analysis of newly acquired ICESat-2 laser altimeter data. We map the position of the landward limit of tidal flexure and the inshore limit of hydrostatic equilibrium, as demonstrated over the mountainous and hitherto difficult to survey grounding zone of Larsen C Ice Shelf. Since the start of data acquisition in 2018, our method has already achieved a near nine-fold increase in the number of grounding zone observations compared with ICESat, which operated between 2003 and 2009. We have improved coverage especially over the previously poorly mapped Bawden and Gipps Ice Rise and Hearst Island. Acting as a reliable proxy for the grounding line, which cannot be directly imaged by satellites, our ICESat-2-derived landward limit of tidal flexure locations agree well with independently obtained measurements, with a mean absolute difference and standard deviation of 0.39 km and 0.32 km, respectively, compared to interferometric synthetic aperture radar-based observations. Our results demonstrate the efficiency, density and high spatial accuracy with which ICESat-2 can image complex grounding zones, and its clear potential for future mapping of the pan-ice sheet grounding zone. We present the results of mapping the grounding zone of the Antarctic Ice Sheet using laser altimetry from the ICESat-2 satellite, based on a combination of repeat track data and crossover analysis of ascending and descending tracks. We use a new automated method to provide estimates for both the landward limit of ice flexure and the inshore limit of hydrostatic equilibrium by detecting the ocean tidal signals, and is demonstrated on the Larsen C Ice Shelf in the Antarctic Peninsula. The results show a 2 times increase in number of observations of the grounding line location compared to ICESat-1, as well as improved precision. The mean absolute separation and the standard deviation between our ICESat-2 derived grounding line and DInSAR grounding line product are 0.29 km and 0.31 km, respectively. The beam pair structure of ICESat-2 enables us to derive the grounding zone features from a minimum of two repeat cycles. Our results demonstrate that ICESat-2 can provide high precision and density observations of grounding line in both space and time. This new method can improve the efficiency of grounding zone calculation and can be applied to other regions of the Antarctic Ice Sheet.

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1 Introduction

Long-term satellite observations have linked the on-going thinning of Antarctic ice shelves (Paolo et al., 2015) with enhanced rates of ice discharge across the grounding line (hereinafter referred to as the GL) - ~~The accelerating mass loss of the Antarctic ice shelves can trigger increases in ice discharge from the grounded ice sheet through the grounding line (hereinafter referred to as GL) and therefore increase contribution to the global sea level rise (Paolo et al. 2015).~~ The GL is the point where the grounded ice sheet first detaches from the bedrock and begins to float (Fricker and Padman, 2006); ~~and where the ice sheet is discharged into the ice shelves and the ocean.~~ Ice discharge calculations are sensitive to the assumed location of the GL and therefore accurate GL ~~location-mapping~~ is required for ~~the~~ mass balance estimates of the grounded ice sheet using the Input-Output Method (IOM) (Chuter and Bamber, 2015; Rignot et al., 2019) ~~(Chuter and Bamber 2015; Rignot et al. 2019)~~. Changes in GL position are a key indicator of ~~changes in the dynamical balance of the ice sheet the Antarctica Ice Sheet mass imbalance (Schoof, 2007)(Schoof 2007)~~. Rapid GL retreat of glaciers in the Amundsen Sea Sector between 1992 and 2011 observed from ERS-1/2 satellite radar interferometry (Rignot et al., 2014) ~~(Rignot et al. 2014)~~, and the accelerating retreat of ~65% of the GL along the Bellingshausen Sea Sector between 1990 and 2015 from Landsat optical images (Christie et al., 2016) ~~(Christie et al. 2016)~~ reflect an ocean-driven glacial mass loss in West Antarctica. Thus, accurate knowledge of the GL position ~~and its changes are~~ is critical for multiple applications including ice sheet numerical modelling (Joughin et al., 2010) ~~(Joughin et al. 2010)~~, mass budget studies (Shepherd et al., 2018) -and assessing ice sheet stability (Favier et al., 2014).

The GL (Point G in Fig. 1) ~~point G in Figure 1~~ lies towards the landward edge of a transition zone between the fully grounded ice sheet (landward limit of tidal flexure shown as Ppoint F in Figure-Fig. 1) and the freely-floating ice shelf (inshore limit of hydrostatic equilibrium shown as Ppoint H in Figure-Fig. 1), forming the grounding zone (hereinafter referred to as the GZ) ~~(Fricker and Padman 2006)~~. Within the GZ, there is Point I which is the break-in-slope where the surface slope changes most rapidly from the flat floating ice to the steep land ice (Fig. 1). ~~Its width depends on ice thickness and rheology as well as the combined effects of bed topography, tidal motion and the GL shape.~~ While Point G cannot be detected directly from satellite-based observations, Point F lies close to this location, and is thus generally considered to be the most robust satellite-observable proxy for Point G (Fricker and Padman, 2006; Fricker et al., 2009; Brunt et al., 2010b; Brunt et al., 2011; Rignot et al., 2011). ~~The GL position is difficult to observe directly because it is at the bottom of the ice sheet. However, the surface features of the GZ, such as the landward limit of tidal flexure of the ice surface (point F in Figure 1) which is the closest detectable surface feature to the true GL point G, mapped by satellite remote sensing techniques, can be used as a proxy for GL position.~~

The most accurate method ~~, to date,~~ for ~~calculating-estimating the Point F landward limit of ice flexure induced by tidal motion~~ is using differential synthetic aperture radar interferometry (DInSAR) (Rignot et al., 2011). This method, however, is constrained by the availability of suitable short temporal repeat pass SAR images, and there are relatively few regions where

60 the method has been applied repeatedly (Friedl et al., 2019; Hogg et al., 2017). It is also limited by the uncertainties in the external DEMs used in the geocoding of SAR images (Friedl et al., 2019; Milillo et al., 2017). Points F and H (Fig. 1) ~~The flexural point F as well as the hydrostatic point H (Figure 1) have~~ previously also been derived using ~~repeat tracks of~~ ICESat-1 laser altimetry data (Fricker and Padman, 2006; Brunt et al., 2010b) (~~Brunt et al. 2010; Fricker and Padman 2006~~) and from pseudo crossovers of CryoSat-2 radar altimetry data (Dawson and Bamber, 2017; Dawson and Bamber, 65 ~~2020~~)(~~Dawson and Bamber 2017~~). Both ~~these~~ methods can provide additional GZ information across regions ~~data for regions~~ where the DInSAR-derived GZ information is unavailable. ICESat-1 repeat track analysis proved to be a robust method for analysing the GZ, but its coverage and temporal resolution were limited due to the requirement of multiple repeat tracks from different campaigns (Fricker and Padman, 2006; Brunt et al., 2010b)(~~Brunt et al. 2010; Fricker and Padman 2006~~). In addition, the approach used for ICESat-based GZ detection relied on visual interpretation, requiring a large amount 70 of manual intervention (Fricker and Padman, 2006; Brunt et al., 2010b; Brunt et al., 2011)~~the detection of GZ from ICESat-1 laser altimetry was based on visual interpretation which required a large amount of manual intervention (Brunt et al. 2010; Brunt et al. 2011; Fricker and Padman 2006)~~. Point I mapped from satellite imagery has also been used to represent Point G (Bindschadler et al., 2011; Scambos et al., 2007), but this method often fails to identify fast-flowing glaciers with low surface slope where the break-in-slope is less pronounced.

75 The launch of ICESat-2 on 15 September 2018, as a successor to the ICESat-1 satellite mission, can achieve higher along-track ~~sampling rates~~~~spatial resolution~~ and better spatial coverage ~~as well as nine times better coverage~~ compared ~~with~~ to its predecessor (Markus et al., 2017), providing the potential to map the GZ with greater accuracy and spatio-temporal coverage (~~Markus et al. 2017~~). ICESat-2 has a repeat cycle of 91 days. ~~ICESat 2 measures the ice sheet surface elevation at a repeat cycle of 91 days (Markus et al. 2017)~~. Compared to the single beam of the Geoscience Laser Altimeter System onboard 80 ICESat, it measures the surface elevation of ice sheets using six beams in three beam pairs emitted from the Advanced Topographic Laser Altimeter System (ATLAS) and enables an instantaneous determination of local across-track slope (Smith et al., 2019). ~~The Advanced Topographic Laser Altimeter System (ATLAS) onboard ICESat 2 has three beam pairs in comparison with the single beam of the Geoscience Laser Altimeter System (GLAS) onboard ICESat 1.~~ The across-track spacing between each beam pair is approximately 3.3 km with a pair spacing of ~90 m. The along track sampling interval of 85 each beam is 0.7 m with a nominal 17 m diameter footprint compared with the 170 m along-track spacing of ICESat-1 (Markus et al., 2017). In this study, we investigate the ability of using ICESat-2 data to map the ~~Antarctic~~ Antarctic GZ ~~GZ~~. ~~and~~ We present a computationally efficient technique to measure Points F and H ~~the flexural point F and hydrostatic point H~~ by analysing repeat track data and crossover data from ascending and descending tracks ~~based on the repeat track data in combination with crossover data from ascending and descending tracks~~. We chose ~~the~~ Larsen C Ice Shelf in the Antarctic 90 Peninsula to test this new methodology. ~~as~~ it is one of the northernmost ice shelves in Antarctica with ~~highest~~ widest across-track spacing ~~and~~ ~~and the largest ice shelf in the Antarctic Peninsula with~~ a range of different surface slopes at the GZ with complex topography inland (Jansen et al., 2010). ~~It is, therefore, an ice shelf that presents a severe test for any new~~

~~approach it also experiences a large average tidal range of ~2 m, which facilitates testing the approach and proving its suitability for being applied to the whole of the Antarctica.~~

95 2 ICESat-2 Data

The first two cycles of ICESat-2 data acquired between 14 October 2018 and 30 March 2019 are not repeat cycles because the spacecraft pointing control was not yet optimized. In this study, we used 10 months of the ICESat-2 Land Ice Along-Track Height Product ATL06 version 3 data spanning from 30 March 2019 to 6 March 2020 (no data existed between 26 June 2019 to 26 July 2019 due to solar array anomaly of the satellite). Within this time period, there are four repeat cycles (3, 100 4, 5 and 6), however, part of cycle 4 (Reference Ground Tracks (RGT) numbered from 0 to 441) were missing and could not be used in this analysis. ~~We used 12 months of the ICESat 2 Land Ice Along Track Height Product ATL06 version 2 data spanning from October 2018 to November 2019 in this study.~~ The ATL06 elevation measurements are derived from the individual photon elevation observations, averaged over a 40 m length segment. The segments overlap by 50% along each of the six ground tracks, thus the ATL06 elevation measurements are separated by 20 m along each ground track (Smith et al., 105 2019). ~~Five cycles exist during the study period but only cycles 3, 4 and 5 are exact repeat cycles. Due to technical issues in the first two cycles, ICESat 2 did not point at the Reference Pair Track (RPT) which is the half way between the predefined locations of two ground tracks that make up a pair. Among all five cycles, three repeat cycles from March 29, 2019 to November 15, 2019 were used in a repeat track analysis for the GZ estimation, while data from all five cycles were used in a crossover analysis by using ascending and descending tracks.~~

110 The method used in this study of estimating GZ features relies on detecting the vertical movement of floating ice due to ocean tides. ICESat elevation data were routinely corrected for ocean and ocean loading tide and had to be ‘re-tided’ (adding tidal corrections back) (Fricker and Padman, 2006). While the ocean tide correction is not applied to the ICESat-2 ATL06 elevation (Neumann et al., 2019),

~~we~~The ATL06 elevation data have been corrected for ocean loading tide, pole tide, and solid earth tide (Neumann et al. 115 2019). ~~Since the method used in this study of estimating GZ features relies on detecting the vertical movements of floating ice due to ocean tides, we did not add the correction for ocean tide and~~ ‘re-tided’ the ocean-loading tide in this study (Fricker and Padman 2006). We used the ATL06_quality_summary flag to remove poor quality elevation measurements, which can be a result of clouds or random clustering of background photons (Smith et al., 2019). ~~T~~We also used the along-track slope parameter was used to perform a height consistency check between adjacent elevation measurements along each ground 120 track. This was achieved by calculating the neighbouring elevations based on the along-track slope and comparing to the original surface elevations for the two neighbouring measurements (Arendt et al., 2019). We only used data where the differences between the original elevations and the estimated elevations were lower than 2 m. In addition, we also derived the locations of every reference segment for each ground track from the segment_quality group of the ATL06 product, which

were used to calculate a reference track in the repeat track analysis in section 3. ~~the surface elevation was also compared with the reference DEM Reference Elevation Model of Antarctica (REMA) (Howat et al. 2019) provided in the ATL06 product. The elevation data were discarded if the elevation differences with REMA fell outside a ± 150 m threshold.~~ The ICESat-2 ATL06 elevation data from repeat cycles 3, 4, 5 and 6 ~~3, 4 and 5~~ on the Larsen C Ice Shelf are shown in Fig. ~~Figure 2~~.

3 Methodology

3.1 Repeat track analysis

130 To identify the GZ features, we adopted a similar approach previously used with ICESat data by measuring the vertical motion of floating ice induced by ocean tides from a set of elevation anomalies for each repeat track (Brunt et al., 2010). The workflow of the repeat track analysis developed in this study includes four steps: 1) Repeat-track data preprocessing (section 3.1.1, box 1 in Fig. 3). 2) Elevation anomaly calculation (section 3.1.2, box 2 in Fig. 3). 3) GZ feature identification (section 3.1.3, box 3 in Fig. 3). 4) Filtering and visual validation (section 3.1.4).

135 3.1.1 Repeat-track data preprocessing

ICESat-2 generates six ground tracks in three beam pairs along one RGT (out of 1387 RGTs) in each repeat cycle (Fig. 1 in Smith et al. (2019)), forming six sets of repeat tracks. Figure 4a shows the four repeat tracks along the left beam in beam pair 1. Along one ground track, the across-track separation between different repeat tracks is approximately 10 m (Fig. 4a). Compared with ICESat data where the repeat track separation can exceed 100 m (Brunt et al., 2010b), this improvement can
140 greatly reduce the errors in elevation change associated with across-track slopes.

For all six ground tracks numbered ‘1l’ (left beam in beam pair 1), ‘1r’, ‘2l’, ‘2r’, ‘3l’, ‘3r’, from different repeat cycles along each of the 1387 RGTs, we firstly obtained the elevation and geolocations of ATL06 measurements, as well as the geolocations of reference segments. We then categorized the derived repeat tracks into distinct repeat-track data groups, each group was marked with a unique beam number and an RGT number. Only the repeat-track data groups (hereinafter referred
145 to as ‘single beam repeat-track data groups’) with two or more repeat tracks were used for GZ calculation. For each single beam repeat-track data group, a ‘nominal reference track’ (black circles in Fig. 4a) at an along-track interval of 20 m was calculated by averaging the locations of reference segments from all repeat tracks. The use of reference segments to obtain the nominal reference track can produce a common set of geolocation profiles free of the data loss of actual ground tracks.

Although we do not expect a substantial across-track slope over a ~ 10 m separation, elevation changes in some high sloping
150 areas may still be affected by across-track slope. In order to reduce the errors in elevation change caused by large across-track slope and facilitate the automation of our repeat track analysis method, we generated three additional repeat-track data groups for each beam pair on top of the six single beam repeat-track data groups. A beam pair repeat-track data group was

created by merging the two single beam repeat-track data groups for the left beam and right beam in one beam pair. Each beam pair repeat-track data group was marked with a unique beam pair number ('1', '2', '3') and an RGT number. For example, the beam pair repeat-track data group shown in Fig. 4b includes all the repeat tracks along both the left beam and right beam in beam pair 1. As with the single beam repeat-track data group, a nominal reference track was calculated by averaging the locations of reference segments from all tracks inside the beam pair repeat-track data group, shown as the black circles in the middle between the left and right ground tracks in Fig. 4b. The elevation of each track was then corrected for across-track slope onto this nominal reference track in section 3.1.2, this can reduce the errors associated with across-track slope. Altogether we have generated nine different repeat-track data groups along one RGT, six for single beam and three for beam pair. The GZ calculation was performed individually inside each repeat-track data group. ~~To measure the vertical motion of floating ice induced by ocean tides, we used a repeat track analysis similar to the approach used with ICESat-1 data by calculating the elevation anomalies for each repeat track (Brunt et al. 2010). However, now using the beam pairs of ICESat-2 we can also apply a cross track slope correction in order to reduce noise caused by rough terrain, which facilitated the automation of GZ mapping. The workflow of the repeat track analysis is shown in Figure 3. It includes two parts: 1) the cross track slope correction of surface elevation and the elevation anomaly calculation; 2) the GZ features estimation from the corrected elevation anomalies.~~

~~At the time of this study, only three exact repeat cycles were available. To maximise the number of repeat tracks to be used in the analysis, we treated two ground tracks that make up a pair from each repeat cycle as individual repeat tracks. This resulted in two repeat tracks per cycle for one beam pair and six repeat tracks for one beam pair from three repeat cycles (Figure 4a). The two ground tracks in a beam pair from one cycle are separated by ~90 m and the separation between same side ground tracks in a pair from different repeat cycles is less than 10 m. This is a marked improvement compared with ICESat-1 where the repeat track separation can exceed 100 m (Brunt et al. 2010). We used the average location of individual RPT from each repeat cycle for one beam pair as the nominal reference track to be used in the repeat track analysis, at an along-track interval of 20 m.~~

3.1.2 Elevation anomaly calculation

Before calculating the elevation anomalies for each track inside the repeat-track data group, a reference GL estimate is needed to define a GZ search window in the calculation (Fig. 3 box 2). For this purpose, we used the ESA Climate Change Initiative (CCI) (ESA Antarctic Ice Sheets CCI, 2017) grounding line derived from the DInSAR observations between 2015 and 2016 as this is the most up-to-date GL maps of Larsen C Ice Shelf. However, this product does not provide complete coverage, so we used the Depoorter et al. (2013) GL to fill in the data gaps and produced a composite GL for Larsen C Ice Shelf. The Depoorter et al. (2013) GL is the most complete grounding line product to date and was compiled from a variety

of GL datasets, including the break-in-slope points mapped from the Landsat-7 optical imagery in ASAlD project between
185 1999-2003 (Bindschadler et al., 2011) and from the MODIS-based Mosaic of Antarctica between 2003-2004 (Scambos et al.,
2007), DInSAR Point F from (Rignot et al., 2011) between 1994-2009, and the ICESat Point F between 2003-2008 (Brunt et
al., 2010b; Brunt et al., 2011).

For each repeat-track data group, the reference GL was calculated as the intersection between the nominal reference track
and the composite GL. Only ATL06 elevation measurements within a window size of 12 km landward and seaward of the
190 reference GL along the nominal reference track were used. The grounding line of Larsen C Ice Shelf is stable and therefore
unlikely to have experienced extensive changes (Konrad et al., 2018), thus the 24 km calculation window is suitable for GZ
calculation in this region. Data points with the elevation higher than 300 m are most likely to be land ice as the surface
elevation of GZ is unlikely to exceed this threshold based on the hydrostatic equilibrium assumption. In order to improve the
calculation efficiency, this part of the data was removed. The ICESat-2 elevation measurements located in open water were
195 also discarded by using the coastline mask provided by the SCAR Antarctic Digital Database (ADD)
(<https://data.bas.ac.uk/items/862f7159-9e0d-46e2-9684-df1bf924dabc/#item-details-data>).

For repeat tracks in a single beam repeat-track data group, the average of elevations of each repeat track at the nominal
reference track was taken as the reference elevation for GZ identification. A set of ‘elevation anomalies’ were estimated by
subtracting the reference elevation from the elevation profiles of each individual repeat track. The elevations and elevation
200 anomalies of four repeat tracks for the right beam in track 1009 beam pair 2 are shown in Figs. 5a and 5b, respectively.

For each track in a beam pair repeat-track data group, we firstly used the across-track slope parameter $\frac{dh}{dy}$ shown in Fig. 4b to
correct the across-track slope induced elevation changes and interpolated to the nominal reference track. The across-track
slope $\frac{dh}{dy}$ for two ground tracks in a beam pair was calculated using the Eq. (1),

$$\frac{dh}{dy} = \frac{h_L - h_R}{y_L - y_R} \quad (1)$$

205 where h_L , h_R are the elevations of left and right ground tracks that make up a beam pair. y_L , y_R are the across-track y-
coordinates measured perpendicular to the RGT for the left and right ground tracks.

The interpolated elevation h_{Ref} at the nominal reference track for the elevation of the left ground track, h_L , was calculated
using the Eq. (2) (same for the elevation of the right ground track, h_R),

$$h_{Ref} = h_L - \frac{dh}{dy}(y_L - y_{Ref}) \quad (2)$$

210 where y_{Ref} is the across-track y-coordinate measured perpendicular to the RGT for the nominal reference track (Fig. 4b). The
average of all the elevations corrected for across-track slope from each track at the nominal reference track was taken as the

reference elevation used in our identification of the grounding zone. After applying the across-track slope correction, a set of elevation anomalies were estimated by subtracting the reference elevation from the elevations corrected for across-track slope of each individual track.

215 3.1.3 GZ feature identification

Point F is identified as the point where the elevation anomaly of each repeat track first becomes significant, while Point H is defined where the elevation anomaly of each repeat track reaches its maximum and becomes consistent with the local tidal amplitudes (Fricker and Padman, 2006). Based on this definition, Points F and H were visually picked from ICESat repeat tracks by Fricker and Padman (2006) and Brunt et al. (2010b).

220 To automate the identification of Points F and H from the elevation anomalies, we first calculated ~~When using the automated repeat track analysis to estimate the GZ features, a reference GL estimate is needed (Figure 3). Here we used Depoorter et al. (2013) GL as it is the most complete grounding line product to date, compiled from all current available data. For the GZ calculation on ice rises and ice rumples, the MEaSURES GL product was used (Mouginot 2017). The initial GL input was calculated as the intersection between the nominal reference track and the reference GL product. Only ATL06 elevation measurements within a window size of 12 km landward and seaward of the initial GL input along the nominal reference track were used. The grounding line of the Larsen C Ice Shelf was stable and therefore unlikely to have experienced rapid changes (Konrad et al. 2018), thus the choice of the above two reference GL products and the 24 km calculation window are suitable for the GZ calculation in this region. In order to improve calculation efficiency, data points with the elevation higher than 300 m were removed as the surface elevation of GZ is unlikely to exceed this threshold based on the hydrostatic equilibrium assumption. The ICESat 2 elevation measurements located in open water were also discarded by using the MEaSURES Antarctic coastline mask (Mouginot 2017).~~

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~~The elevation change calculated from repeat tracks is a combination of cross-track slope induced elevation change and temporal elevation changes such as snow accumulation or ablation, and vertical tidal displacement. As only 8 months of repeat cycles from March to November 2019 were used, temporal elevation changes due to snow accumulation or ablation were likely to be minimal and were disregarded in this study. Elevation change due to ocean tides is the only factor needs to be considered when estimating GZ, thus the elevation change caused by large cross-track slope in high sloping areas can make it difficult to extract the GZ features (Moholdt et al. 2010). Here we used the cross track slope parameter $\frac{dh}{dy}$ shown in Figure 4a to correct the cross-track slope induced elevation changes and interpolated to the nominal reference track. We calculated the interpolated elevation $h_{LL,Ref}$ at the nominal reference track for the elevation of one ground track, $h_{LL,G}$ using the Eq. (1),~~

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$$h_{LL,Ref} = h_{LL,G} - \frac{dh}{dy} (y_{ATC,G} - y_{ATC,Ref}) \quad (1)$$

where the cross-track slope $\frac{dh}{dy}$ for two ground tracks in a beam pair was calculated using the Eq. (2);

$$\frac{dh}{dy} = \frac{h_{LL,L} - h_{LL,R}}{y_{ATC,L} - y_{ATC,R}} \quad (2)$$

245 $h_{LL,L}$, $h_{LL,R}$ are the elevations of left and right ground tracks that make up a beam pair. $y_{ATC,L}$, $y_{ATC,R}$ and $y_{ATC,Ref}$ are the y coordinates measured perpendicular to the Reference Ground Track (RGT) for the left and right ground tracks, and the nominal reference track (Figure 4a), respectively. The average of all cross-track slope corrected elevations from each repeat track at the nominal reference track was taken as the reference elevation in GZ estimation. We also only used data where there were at least four repeat tracks.

250 After the cross-track slope correction for each ground track in a pair, a set of ‘elevation anomalies’ were estimated by subtracting the reference elevation profile from the cross-track slope corrected elevation profiles of each individual repeat track, which are shown as the color-coded dot curves in Figure 5b. The elevation anomalies calculated from the original surface elevation without cross-track slope correction are shown in Figure 5a as color-coded dot curves for comparison. To estimate the flexural point F and hydrostatic point H from the elevation anomalies after cross-track slope correction, the Mean Absolute Elevation Anomaly (MAEA) (Figure 5c) was calculated from corrected elevation anomalies by averaging
255 the absolute values of each elevation anomaly profile (Fig. 5c) shown in Figure 5b. We defined

The flexural point F is the landward limit of ice flexure from tidal motion (Fricker and Padman 2006). The region where the MAEA is close to zero (the region to the left of point F in Figure Fig. 1) is regarded as the fully grounded ice. Point Based on this definition, the flexural point F was then estimated to be the point where the gradient of the MAEA first increases from zero, and the second derivative of the MAEA reaches its positive peak (Figure 5e). To reduce the influence of small-scale noise on the MAEA curve during the extraction of GZ features, a Butterworth low-pass filter with a normalized cut-off frequency of 0.032 and an order of 5 was applied (solid grey line in Fig. 5d). The low-pass filter removed the high-frequency noise without changing the shape of the MAEA curve therefore it won't influence the local transition points. A set of multiple peaks were then extracted from the second derivative of the filtered MAEA. Despite the low-pass filter, noise still existed especially in the areas with complex topography, resulting in multiple peaks not associated with the GZ
260 features. In order to select the correct peaks corresponding to the GZ features of interest, we fitted an Error function weighted by a Gaussian function with the variance of 0.005 to the MAEA (solid yellow line in Fig. 5d). The peak from the third derivative of the Error function at the landward region is a good measure of the approximate location of Point F, therefore, it was used as a guide point The transition point from this ideal sigmoid curve was used as a guide to select the correct peak and find the GZ features. The closest positive peak (from the second derivative of filtered MAEA) to this guide
270 point was identified as Point F. This allows the process to be automated in comparison to ICESat-1.

Similarly to the definition by Fricker and Padman (2006), we defined Point H as the point

The hydrostatic point H is the inshore limit of the floating ice shelf that is in hydrostatic equilibrium (the region to the right of point H in Figure 1) (Fricker and Padman 2006). It is also where the elevation anomalies are consistent with the local tidal amplitudes and the MAEA reaches a maximum and becomes, becoming stable, which is The hydrostatic point H is then estimated to be the transition point where the gradient of the MAEA finally decreases to zero and the second derivative of the MAEA reaches its negative peak (Figure 5e). To reduce the influence of small-scale noise on the MAEA curve during the extraction of GZ features, a Butterworth low-pass filter with a normalized cut-off frequency of 0.016 and an order of 5 was applied (Figure 5d). In order to select the correct peaks corresponding to GZ features, we fitted an error function weighted by a Gaussian function with the variance of 0.005 to the MAEA (Figure 5d).

To find the flexural point F, we used the closest positive peak (from the second derivative of filtered MAEA) to the peak from the third derivative of the error function curve. Unlike the abrupt change in the gradient of the elevation anomaly at point F, the gradient often tends slowly to zero at point H (Brunt et al., 2010b; Dawson and Bamber, 2020) (Figure 5a and 5b) (Brunt et al. 2010). Therefore, using the same approach that we used for Point F, for as F to find Point H results in its location being slightly landward (vertical dashed grey line in Fig. 5d) compared with the real GZ signal.

Instead Consequently, we used the peak from the fourth derivative of the Error function curve as the guide point. This point is closer to the transition point where the MAEA gradient finally decreases to zero, and the closest negative peak of the second derivative of filtered MAEA was used as point H. Additionally, the tidal height predictions at 10-5 km offshore from the reference GL for each repeat track were calculated from the CATS2008 Tidal Model, which is an update to the model described by Padman et al. (2002). The tidal heights provide an independent check for the tide-induced surface elevation changes at point H. In order to assess the reliability of our GZ features in terms of the combined effect of tidal range and data coverage, the number of repeat cycles used in the GZ calculation and the mean tidal amplitude at Point H from the MAEA curve were also recorded.

3.1.4 Filtering and visual validation

Our algorithm is designed to take in both the single beam and beam pair repeat-track data groups as input, and produce a set of Points F and H in whatever conditions, to account for complex geographic features in different GZ regions. However, the GZ results can be filtered by applying a set of quality check flags.

The correct identification for GZ features depends on the accurate fitting of the Error function, which can be influenced by noise in elevation anomalies caused by across-track slope and small scale topographic features such as crevasses. Also the filtered bad elevation measurements due to snow and cloud in pre-filtering steps in section 2 can cause significant data gaps for some repeat-track data groups, making it impossible to identify the correct GZ features. To identify these failures in the approach, we applied two quality check flags. The first flag is data loss percentage. If the percentage of segments on the nominal reference track where there is no elevation measurement is larger than 50%, then it means this repeat-track data

group does not have enough data to perform a reliable GZ calculation and the calculated GZ features were marked as 'Quality-1'. The second flag is inaccurate Error function fitting. Although noise in elevation anomalies related with across-track slope has been greatly reduced by using a single beam repeat-track data group over ~10 m separation and applying an across-track slope correction, the remaining across-track slope can still introduce errors for some repeat tracks. Together with crevasses, they can introduce a significant amount of noise in the MAEA curve and influence the final Error function fitting. The most prominent characteristic of this inaccurate Error function fitting, is the calculated Point F often locates several kilometres away from the reference GL. Here we calculated the distance between Point F and the reference GL, if it exceeded 5 km then this GZ was marked as 'Quality-2' to indicate potential Error function fitting problems. These two quality flags highlight the majority of incorrectly identified GZ features. The remaining results which passed the quality checks were marked as 'Quality-0', indicating these GZ features are potential good results.

However, there are several circumstances where quality flags are inaccurate, so we performed a final visual validation on all the GZ results with the aid of the flags. For example, the GZ results marked with 'Quality-2' can be the existence of ice plain, which can result in up to 10 km separation between Point F and the reference GL (Brunt et al., 2011). Also, in category 'Quality-0', large across-track slopes can cause inaccurate GZ identification for single beam repeat-track data group (Figs. 6a-6d), but not for the beam pair repeat-track data group (which includes an across-track slope correction, Figs. 6e-6h). To improve these results, we can manually set a new calculation window which only captures the ocean tidal signal. However, this requires more manual intervention, and does not significantly improve the coverage, as the nominal reference track of the beam pair repeat-track data group is only ~ 45 m away from either the left or right beam. Thus, inaccurate GZ data due to large across-track slope for single beam repeat-track data group were removed in the final visual validation.

3.2 Crossover analysis

Changes in ice shelf elevation due to tidal variation also can be calculated at the crossovers from ascending and descending tracks (Fig. 4c)(~~Figure 4b~~). Similarly to repeat track analysis, the elevation changes at crossovers on floating ice caused by tidal movement will be high, while they are close to zero on land ice where there is no vertical movement caused by ocean tides. Therefore, the elevation change from the crossover analysis can provide additional information on the GL location.

The crossover location was calculated by fitting latitude-longitude coordinates of all measurements from each ascending and descending track into two quadratic functions and calculating the intersection of these two functions. Only data in proximity to the crossover location were used. We ~~To calculate the elevation change at these crossovers, we~~ first found the two closest observations from the ascending track and the descending track close to the crossover location using a KDTree (k-dimensional tree) ~~using a KDTree~~ within a 100 m searching radius ~~from the ascending track and the descending track~~. We then extracted all the elevation measurements within a 100 m searching radius of these two closest data points from each ascending track and descending track, then calculated the actual location of crossover. The elevation at the crossover was

335 estimated by linearly interpolating the elevations ~~from~~ for each ascending and descending track. If the ~~valid~~-ATL06 elevation measurements did not exist on both sides of the crossover within the 100 m searching distance, then the crossover ~~of this track~~ was discarded (Brenner et al., 2007).

340 ~~TSimilar to repeat track analysis,~~ the elevation change at the crossover not only includes the ocean tidal signal, but also a temporal signal of elevation change. In this study, ~~as we are~~ were only considering crossovers with a time difference less than 91 days to ~~eliminate~~ reduce the influence of temporal elevation change. ~~In addition, we deleted the crossovers where the elevation difference exceeded 10 m to remove other errors such as the geolocation errors of ICESat-2 (Smith et al., 2020)~~we removed the crossovers where the elevation exceeded 20 m. For crossovers on floating ice, if the time stamps of the ascending and descending tracks at the crossover are in the same phase of ocean tide cycle, the elevation change at this crossover should be close to zero, ~~and it will be~~ making it difficult to determine if the ice is floating or not. To eliminate these occurrences, the CATS2008 Tidal Model (Padman et al., 2002) was used to calculate the tidal amplitude changes at each crossover and they were used as a reference for the vertical movements of floating ice. ~~As the minimum detectable tidal amplitude from repeat track analysis is 20 cm after analysing all the GZ features calculated in section 3.1, we then set the minimum threshold of elevation change due to ocean tides on floating ice measured by the crossover analysis to be 40 cm by doubling the 20 cm threshold of repeat track analysis. We extracted the minimum detectable tidal amplitude from the repeat track analysis to be 20 cm based on the results in section 4, and set the minimum threshold of the elevation change due to~~ocean tides on floating ice measured by the crossover analysis to be 40 cm. If both the modelled tidal amplitude and the elevation change at crossover are lower than this threshold, the ascending and descending tracks are likely to be in the same tidal phase and this crossover was discarded. ~~For crossovers calculated from different cycles at the same location, we also averaged the elevation differences at each crossover location.~~

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4 Results and discussion

355 4.1 GZ distribution

Using the newly developed ICESat-2-based GZ detection algorithm in this study, we identified 253 Point F and 263 Point H over Larsen C Ice Shelf, which is a near nine-fold increase in the number of GZ features identified by ICESat (30 of each point (Brunt et al., 2010)). The spatial distribution of GZ features calculated from both ICESat and ICESat-2 are shown in Figs. 7a and 7b, together with a comparison of Point F determined from independent DInSAR observations from the ESA CCI product (ESA Antarctic Ice Sheets CCI, 2017) and Point H identified from Landsat-7 imagery in combination with ICESat data from ASAIID project (Bindschadler et al., 2011) (Figs. 7c and 7d). The number of repeat cycles used to identify the GZ features from each repeat-track data group is shown in Fig. 7e and the mean tidal amplitude at ICESat-2-derived Point H is shown in Fig. 7f. The improvement in our ability to identify the GZ using ICESat-2 data is especially notable in heavily crevassed regions such as Jason Peninsula and Churchill Peninsula (Jansen et al., 2010), which were previously

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365 difficult to identify using ICESat observations alone. ICESat-2-derived Point F provides additional coverage in Hearst
 Island, Gipps and Bawden Ice Rise where ESA CCI DInSAR Point F is not available. Among these three regions, Gipps and
 Bawden Ice Rise are important pinning points for Larsen C Ice Shelf (Borstad et al., 2017).

Among all the ICESat-2-derived GZs, 162 Point F and 169 Point H were calculated from single beam repeat-track data
 groups, while 91 Point F and 94 Point H were calculated from beam pair repeat-track data groups. As the left and right
 370 beams are only separated by about 90 m and the GZ identified from the repeat track analysis for beam pair often locates in
 the middle between the left and right beams (~45 m in either direction), we do not expect there exist large deviations
 between these three GZs. In the same beam pair, we compared the locations of GZs calculated along the left beam and the
 right beam, and compared the GZ locations calculated from the beam pair repeat-track group and the two single beam repeat-
 track data groups. The mean absolute separations and standard deviations are shown in Table 1. The standard deviation
 375 between the locations of Point F at left and right beams is only 60.2 m, while the standard deviation of Point F between the
 single beam and the nominal reference track in the middle of the beam pair is 94.4 m. For Point H, the standard deviations
 for these two comparisons are 349.3 m and 398.6 m, respectively. The similar magnitude in mean absolute separations and
 standard deviations between the GZs calculated from single beam repeat track analysis and beam pair repeat track analysis
 indicates these two methods having good internal consistency in identifying the GZs from ICESat-2.

380 Table 1. Mean absolute separations and standard deviations between the GZ features calculated from single beam repeat-
 track data group and beam pair repeat-track data group.

	Point F		Point H	
	Mean absolute separation (m)	Standard deviation (m)	Mean absolute separation (m)	Standard deviation (m)
Left beam vs Right beam	156.5	60.2	382.2	349.3
Single beam vs Beam pair	141.4	94.4	340.9	398.6

4.2 Comparison with other GZ products

The locations of Point F calculated from ICESat-2 data are in good agreement with the ESA CCI DInSAR Point F (Fig. 7a).
 The absolute mean separation (which was measured as the perpendicular distance from ICESat-2 Point F to DInSAR Point F
 385 line segment), and the standard deviation between ICESat-2 Point F and ESA CCI DInSAR Point F are 0.39 km and 0.32
 km, respectively (Table 2). In comparison, the standard deviation between CryoSat-2-derived Point F and the ESA CCI
 DInSAR Point F is 1.2 km in the same region (Dawson and Bamber, 2020). The absolute separations between the ESA CCI
 DInSAR Point F and ICESat-2 Point F are shown in Fig. 7c, where 65% of ICESat-2-derived Point F are located less than
 0.5 km away from the DInSAR Point F. In addition, we compared our ICESat-2-derived Point F with the break-in-slope
 390 point estimated from the Landsat-7 imagery in ASAlD project (Bindschadler et al., 2011). The break-in-slope point

identified from optical imagery is free from the typical geocoding errors of SAR images in steep terrain especially when using a low quality DEM. Moreover, Larsen C Ice shelf is a relatively slow flowing region so the ASAID break-in-slope point is a good representation of the GL. The absolute mean separation and standard deviation between these two products are 0.34 km and 0.28 km, respectively. The overall separations in Churchill and Kenyon Peninsula are smaller than the ESA CCI DInSAR Point F (Fig. A1).

ICESat-2-derived Points F located inside the inlet at Churchill Peninsula have the largest deviations from ESA CCI DInSAR Point F (Figs. 7a and 7c), with an average of 2.78 km. The differences in position are not because of the incorrect interpretation of Point F from ICESat-2 data but likely due to the existence of a lightly grounded ice plain with low surface slope. Repeat track analysis for the two right beams from cycles 3 and 4 along track 506 beam pair 1 in this region (Fig. 2) is shown in Fig. 8. We manually defined the first break-in-slope of the surface elevation as the ‘coupling point’ in Fig. 8a (grey solid vertical line) (Corr et al., 2001). Between this coupling point and the ICESat-2-derived Point F, no tide-induced elevation change is observed from the elevation anomalies in Fig. 8b. The elevation change signal around the coupling point in the elevation anomalies are the errors associated with across-track slope. We interpreted the region between these two points as an ice plain according to Brunt et al. (2011). Point F can migrate several kilometres with ocean tides due to low surface slope inside the ice plain (Brunt et al., 2011) and low tidal amplitudes (~20 cm, Figs. 7f and 8b) in this region can place the GL position slightly seaward. Therefore, different locations between ICESat-2-derived Point F and the reference GL (ESA CCI Point F in October 2016 in this region) are possibly caused by different ocean tidal amplitudes. In addition, proving our method works at a 20 cm scale tidal amplitude in a region with complex relief demonstrates the ability for the generation of GLs for the majority of the Antarctic Ice Sheet, from regions with low tidal ranges such as the Amundsen Bay Embayment (< 1 m) to regions with large tidal range such as the Ross Ice Shelf (~1 m – 2 m) and the Filchner-Ronne Ice Shelf (> 4m) (Padman et al., 2002).

On Hearst Island, several Points F were identified from ICESat-2 data. Although no ESA CCI DInSAR Point F is available in this region for comparison, we mapped the distributions of the absolute elevation changes, $|dh|$, at crossovers (Fig. 9). The transitions from land ice (low $|dh|$) to floating ice (high $|dh|$) observed from the crossovers align well with the break-in-slope from the REMA slope map and the distribution of ICESat-2-derived Point F from our repeat track analysis (black dots in Fig. 9). Note the Point F, indicated by the black arrow in Fig. 9, is located slightly landward compared to the REMA break-in-slope. The $|dh|$ of nearby crossovers show a similar pattern, with the transition point between red and blue points locating slightly landward of the REMA break-in-slope. The combination of repeat-track-derived Point F and the distribution of crossover $|dh|$ in this region shows that break-in-slope cannot always effectively represent the actual GL even in high-slope and slow-moving areas. Although the spatial separation between crossovers (Fig. 9) (~3 km in Hearst Island) is far larger than the 20 m along-track separation afforded by repeat track observations, surface elevation changes derived from ICESat-2 crossover data can still provide valuable information about the approximate location of grounding zone. In doing so, this

method has the potential to provide important validation of repeat-track-derived GZ features, including fast flowing ice streams where the GZ can undergo rapid changes (Rignot et al., 2011). As one of the northernmost ice shelves in Antarctica, Larsen C Ice Shelf is subject to the highest across-track spacings. Higher density of crossovers will be available further south on the larger ice shelves (e.g. ~ 6 per km^2 on the Ross Ice Shelf) as a result of decreased across-track spacing.

The hydrostatic point H mapped from ASAILD project by combining ICESat-derived Point H and Landsat-7 imagery is the most complete product for Point H to date (Bindschadler et al., 2011), with a positional error of about 2 km. The absolute mean separation and standard deviation between ICESat-2-derived Point H and ASAILD Point H (Figs. 7b and 7d) are 1.2 km and 0.98 km (Table 2), respectively. 83% of ICESat-2-derived Point H locate less than 2 km away from the ASAILD Point H (Fig. 7d), which is within the geolocation error of ASAILD Point H. The largest deviations occur in Joerg Peninsula (Fig. 7d), which is likely that ASAILD Point H is in error here as it fails to capture the concave shape of GZ in this region as shown from the ESA CCI DInSAR Point F in Fig. 7a.

Table 2. Absolute mean separations and standard deviations between ICESat-2-mapped GZ with ESA CCI DInSAR Point F, ASAILD Point I and ASAILD Point H.

		Absolute mean separation (km)	Standard deviation (km)
Point F	DInSAR Point F	0.39	0.32
	ASAILD Point I	0.34	0.28
Point H	ASAILD Point H	1.2	0.98

At the time of this study, only four repeat cycles were available and about a third of the GZ were calculated from two repeat cycles (Fig. 7e). Changes in ocean tide amplitude can induce short-term changes of grounding line position up to 4 km at different tidal levels (Milillo et al., 2017), depending on the acquisition time of the repeat cycles. Although this short-term tidally induced GL migration is not significant over the long observation period with large GL retreat (Rignot et al., 2014), it may hide the real GL retreat signal on a sub-annual scale (Milillo et al., 2017). The capability of our method of identifying the GZ using only two repeat cycles can be used to detect the short-term GL changes caused by ocean tides, and allows us to distinguish the actual GL retreat signal from this tidally induced GL migration with more ICESat-2 repeat cycles available in future.

4.3 Grounding zone width

The width of the GZ depends on ice stiffness, bed slope and ice thickness (Bindschadler et al., 2011), and is useful in determining the ice thickness and rheology across the grounding zone (Dawson and Bamber, 2020). Since the orientation of ICESat-2 ground tracks are not always perpendicular to the GL, calculating the along-track distance between Points F and H as the GZ width can overestimate the actual value. Here we adopted a similar method used in Brunt et al. (2010b) by converting the along-track distance to the cross-GL distance. By assuming that the reference GL generated in section 3.1.2

450 provides a good reference for the local orientation of the actual GL, we calculated the GZ width at each Point F to be the length of the perpendicular line from Point H to the tangent line of the reference GL at the intersection between the nominal reference track and this reference GL. The width of 221 GZs were calculated in this study (Fig. 10), which varies from 0.31 km to 11.62 km with an average of 2.51 km, and the standard deviation is 1.61 km. The distribution of GZ width agrees well with the CryoSat-2-derived GZ width shown in the Fig. 6d of Dawson and Bamber (2020). Similarly to the GZ width 455 distribution on Filchner-Ronne Ice shelf from ICESat (Brunt et al., 2011), there is only one GZ width exceeding 10 km. This GZ locates inside a concave inlet of a glacier in Churchill Peninsula (Fig. 10). The large GZ width could be related to the ice thickness and geometry of GL in this location, but a detailed investigation of the underlying reasons exceeds the research scope of this study.

56 Conclusion

460 We have presented a new, fully automated method of mapping GZ features including Points F and H from ICESat-2 repeat track and crossover data. This method addresses the issue of residuals in elevation change caused by large across-track slopes and the results are partially validated by a crossover analysis of ascending and descending tracks. Using a 10-month period of ICESat-2 ATL06 data spanning from March 2019 to March 2020, we are able to map the majority of the grounding zone in Larsen C Ice Shelf, including highly crevassed regions such as Jason Peninsula and Churchill Peninsula, and the 465 rarely investigated regions such as Bawden and Gipps Ice Rise, which are the important pinning points for Larsen C Ice Shelf. 253 Point F and 263 Point H were identified in Larsen C Ice Shelf, representing a near nine-fold increase compared with the GZ features mapped from ICESat. Our ICESat-2-derived GZ features agree well with previous measurements. The mean absolute separation and the standard deviation between ICESat-2-derived Point F and ESA CCI DInSAR Point F are 0.39 km and 0.32 km, respectively. The mean absolute separation and the standard deviation between ICESat-2-derived 470 Point H and ASAD Point H are 1.2 km and 0.98 km, which are within the ~ 2 km positional error of ASAD Point H. The lowest tidal range, detected by our method on Larsen C Ice Shelf is ~ 20 cm, making it possible to apply the repeat track analysis to other regions with low tidal range, such as the Amundsen Sea Embayment. In addition, the ability of mapping the GZ using only two repeat cycles should allow the detection of short-term GL changes caused by ocean tides and the separation between the long-term GL retreat signal from the short-term tidally induced GL migration when more repeat 475 cycles are available in future. Although the distribution of elevation change from a crossover analysis depends on the across-track spacing of ICESat-2 ground tracks, the example of Hearst Island indicates that the crossover analysis can show the approximate location of the GZ. With smaller across-track spacings in southern regions of the Antarctic Ice Sheet, similar crossover-based analyses have the potential to provide more accurate depictions of the GZ. ~~We have presented a new method to calculate the flexural point F and the hydrostatic point H of the GZ by determining the limits of tidal flexure using a repeat track analysis in combination with crossover analysis of ascending and descending tracks from ICESat 2. This method addresses the issue of residuals in the elevation change caused by large cross-track slopes and enables an automated GZ~~

estimation from a minimum of two repeat cycles. By using three repeat cycles during 8 month period between March 29, 2019 to November 15, 2019, we were able to calculate 69 flexural point F and 71 hydrostatic point H on the Larsen C Ice Shelf. It greatly improves the coverage of the GZ features compared with the ICESat-1 GL and shows the potential of a long time-series monitoring of the GL changes with more repeat cycles being released. The small mean absolute separation 0.29 km and standard deviation of 0.31 km between the ICESat-2 derived GL and the DInSAR GL (Rignot 2016) show an improved precision of the GL estimation compared with the ICESat-1 and CryoSat-2 altimetry data. The lowest tidal range detected by this method on the Larsen C Ice Shelf is ~20 cm, making it possible to apply the repeat track analysis to other regions with low tidal range such as the Amundsen Sea Embayment. Although the distribution of elevation change from crossover analysis depends on the cross-track spacing of ICESat-2 ground tracks, it still shows a good match with the GL calculated from the repeat track analysis. With smaller cross-track spacings in southern regions of the Antarctic Ice Sheet, the crossover analysis should provide better results regarding the GL location. The GZ mapping on the Larsen C Ice Shelf based on ICESat-2 data presented in this study shows an improved coverage and precision of GZ delineation and also indicates the ability for repeat observations of the GZ changes, this will significantly improve our understanding of the Antarctic GZ and its evolution in time with respect to climate and ocean forcing.

Data availability. The ICESat-2 data and ICESat grounding line data used in this study are available from the National Snow and Ice Data Center (NSIDC). The datasets generated in this study are available from the authors upon request.

500 *Author contribution.* TL developed the methods and wrote the paper. GJD and SJC assisted with data processing. JLB conceived the study. GJD and JLB contributed to the interpretation of the results. All authors commented on the manuscript.

Competing interests. The authors declare no competing interest.

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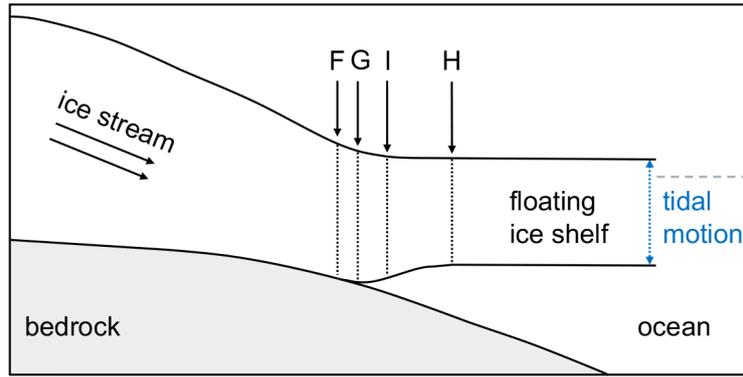
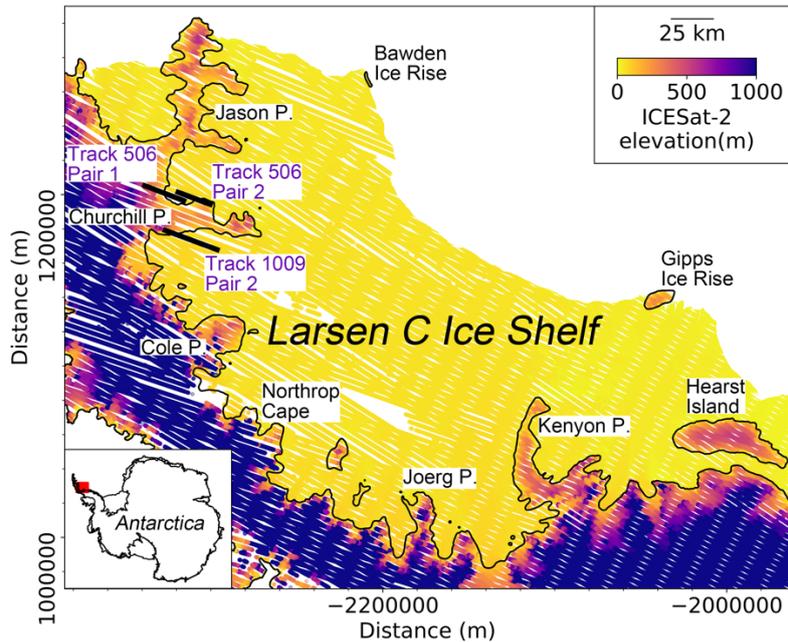
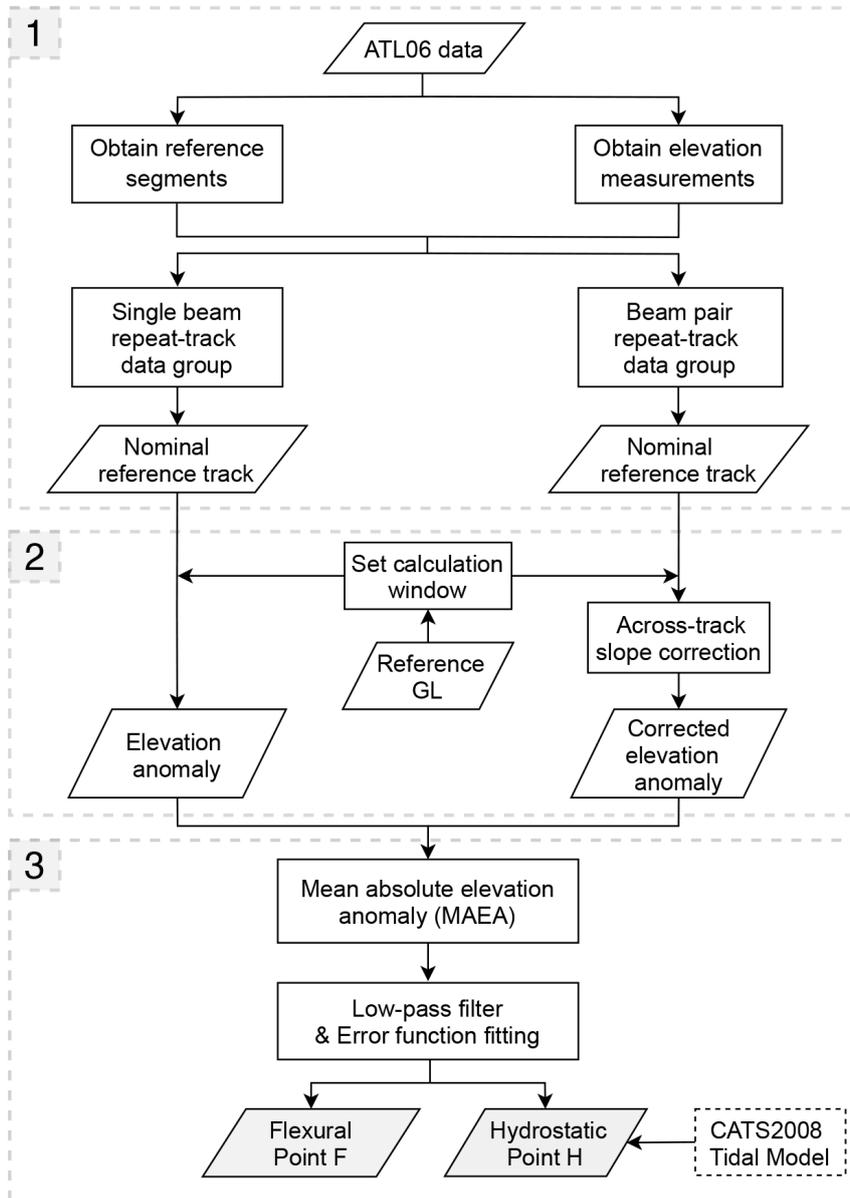


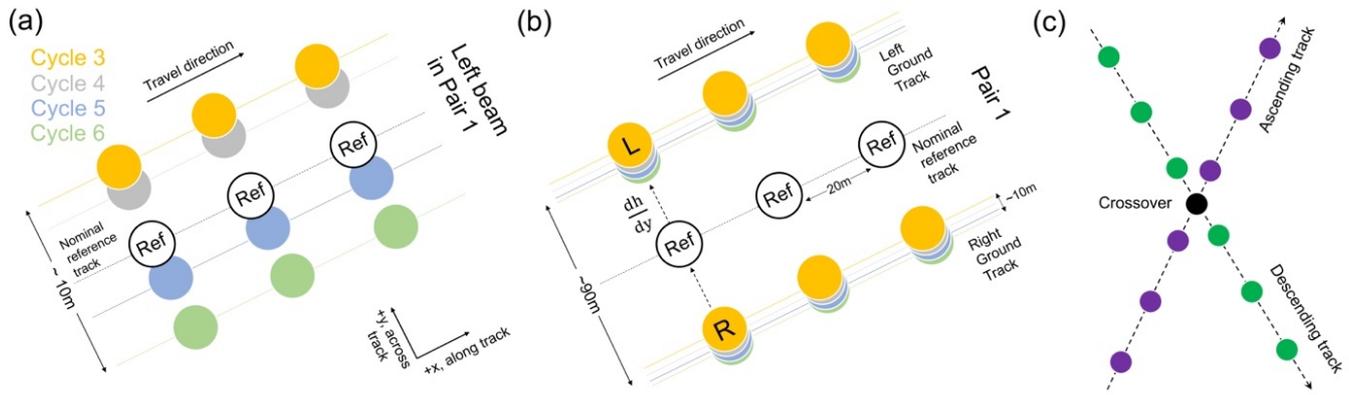
Figure 1. Schematic of the ice shelf grounding zone structure adapted from Fricker and Padman (2006). Point G is the **true grounding line limit of ice flotation**, Point F is the landward limit of ice flexure induced by tidal motion, Point H is the seaward limit of ice flexure and the inshore limit of hydrostatic equilibrium, Point I is the break in surface slope.



610 Figure 2. Locations and surface elevations of ICESat-2 ground tracks from repeat cycles 3, 4, ~~and 5 and 6~~ on ~~the~~ Larsen C Ice Shelf in Antarctic Polar Stereographic (epsg:3031) projection. ~~The black line is the GL calculated from DInSAR data (Rignot 2016).~~ ~~The black line is the GL from Depoorter et al. (2013)~~ ~~The black line is the GL~~ ~~calculated from DInSAR data (Rignot 2016).~~ Red box on the inset map shows the location of ~~the~~ Larsen C Ice Shelf ~~in Antarctica~~.



615 **Figure 3. The ICESat-2 repeat-track workflow used to identify the grounding zone (GZ) in this study, including the limits of inland tidal flexure (Point F) and hydrostatic equilibrium (Point H). Workflow of repeat track analysis in estimating the GZ features including point F and point H.**



620 **Figure 4. Schematics for repeat track analysis and crossover analysis. a) Repeat track analysis method for left beams in beam pair 1 (out of 3 beam pairs) from four repeat cycles 3, 4, 5 and 6. Black circles are the nominal reference tracks showing six repeat tracks from three repeat cycles 3, 4 and 5 for beam pair 1, including both left and right ground tracks in one beam pair from each repeat cycle. Black dots are the nominal reference track. b) Repeat track analysis method for both left and right beams in beam pair 1 from four repeat cycles. Within each repeat cycle, elevations of both two beams ground tracks in a pair were corrected for across-track slope onto the nominal reference track in the middle. c) Crossover method showing the interpolation along the ascending track (yellow-purple dots) and the descending track (blue-green dots) to their intersection as the crossover (black dot).**

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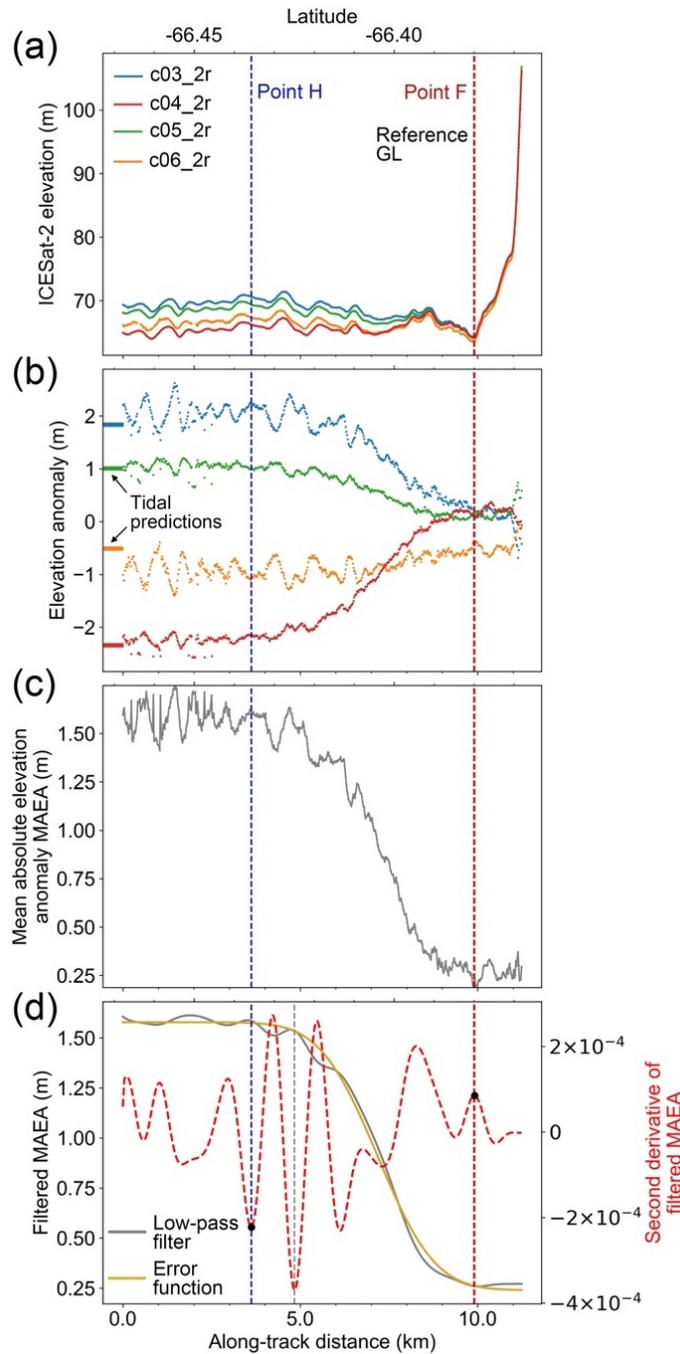
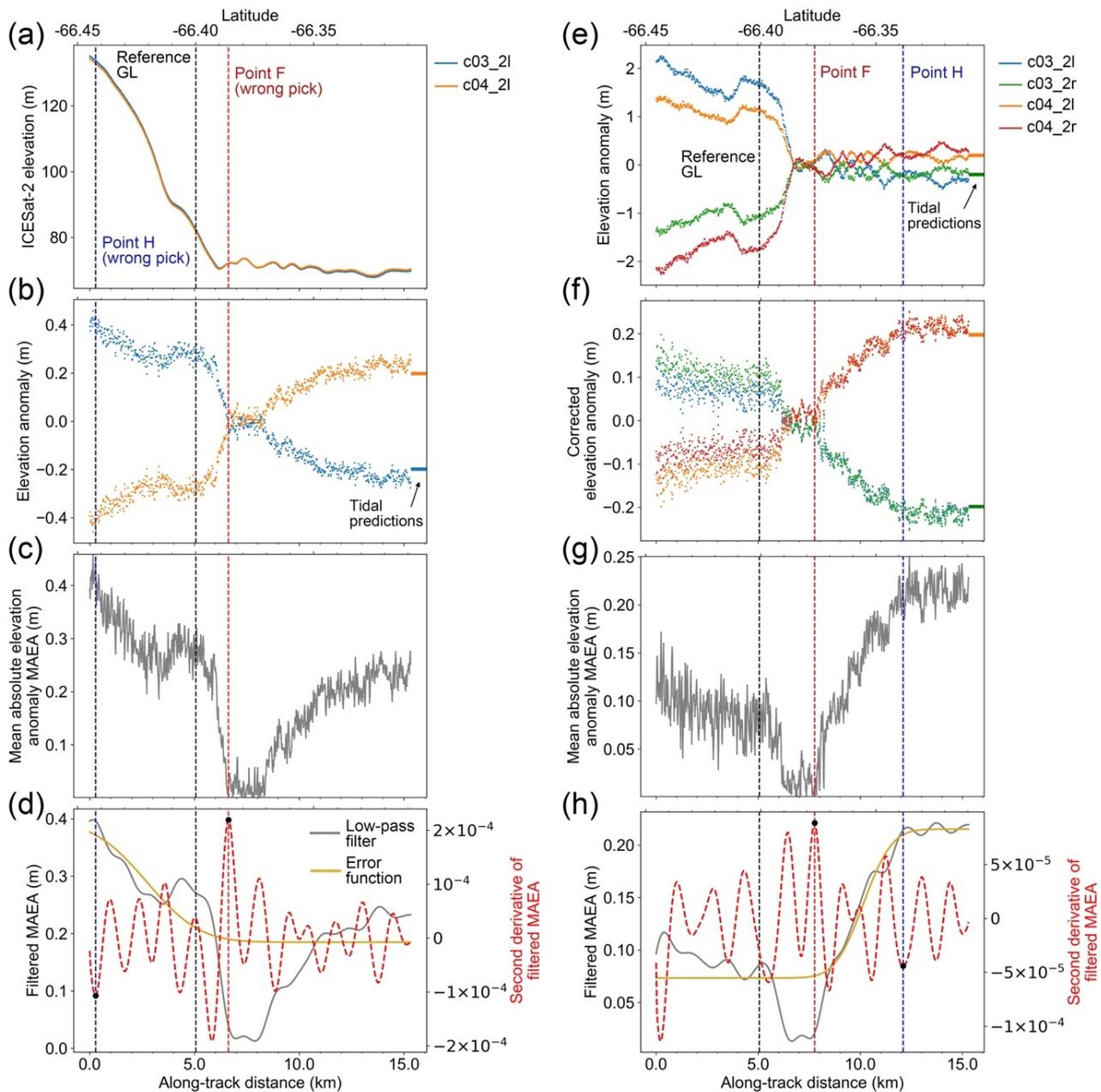


Figure 5. ICESat-2 repeat track analysis for four right beams from repeat cycles 3, 4, 5 and 6 in beam pair 2 of track 1009. The location of track 1009 beam pair 2 is shown in Figure 2. a) ICESat-2 ‘re-tided’ elevation profiles. c03_2r in the legend refers to the right beam of beam pair 2 in repeat cycle 3. b) The elevation anomalies of each repeat track. Horizontal lines at the left are the zero mean tide height predictions from the CATS2008 Tidal Model (Padman et al., 2002) following Fricker and Padman (2006). c) The Mean Absolute Elevation Anomaly (MAEA). d) Low-pass filter filtered MAEA is shown in grey solid line, Error function

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635 fitting of the MAEA is shown in yellow solid line, the second derivate of low-pass filter filtered MAEA is shown in red dashed
curve, the black dots are the locations of inland limit of tidal flexure Point F (right) and inland limit of hydrostatic equilibrium
Point H (left), the vertical dashed grey line is the location of Point H when using the third derivate of Error function as the guide
point. Locations of Point F, Point H and reference grounding line (GL) are marked as the vertical dashed red line, vertical dashed
640 blue line and vertical dashed black line in all subplots. ~~Figure 5. ICESat-2 repeat track analysis of beam pair 1 of track 1192 from
repeat cycles 3 and 4, the location of the track 1192 is shown in Figure 2. Each repeat track is denoted with the cycle number,
beam pair number and the ground track location in right ('r') or left ('l'), e.g. 'e03_1r' is the right ground track in beam pair 1
from cycle 3. a) ICESat 2 're-tided' elevation profiles vs along track distance and latitude (transparent dashed curve in colours
listed in the legend on the right). The elevation anomalies of each track is colour coded point line. b) ICESat 2 're-tided' elevation
profiles and the corrected elevation anomalies after cross track slope correction. Horizontal lines at the right on Figures 5a and 5b
are the zero mean tide height predictions from the CATS2008 Tidal model (Padman et al. 2002). c) The Mean Absolute Elevation
Anomaly (MAEA) by calculating the mean absolute value of all corrected elevation anomalies shown in Figure 5b. d) Low pass
645 filter filtered MAEA is shown in blue line, error function fitting of the MAEA is shown in yellow line, the second derivate of low-
pass filter filtered MAEA is shown in red dashed curve, the black dots are the locations of flexural point F (left) and hydrostatic
point H (right). The location of point F is marked as the vertical dashed red line in all subplots, the location of point H is marked
as the vertical dashed blue line in all subplots, and the location of reference GL from Mouginot (2017) is marked as the vertical
dashed black line.~~



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Figure 6. Comparison between repeat track analysis for single beams and beam pairs. a-d) ICESat-2 repeat track analysis for two left beams from repeat cycles 3 and 4 in beam pair 2 of track 506. The location of track 506 beam pair 2 is shown in Figure 2. Same as Figure 5, but showing the wrong grounding zone (GZ) features picked by repeat track analysis due to large across-track slope on land ice. e-f) ICESat-2 repeat track analysis for both left and right beams in beam pair 2 of track 506 from repeat cycles 3 and 4. e) The elevation anomalies of each track. f) The corrected elevation anomalies after across-track slope correction. g) and h) same as Figure 5c and 5d.

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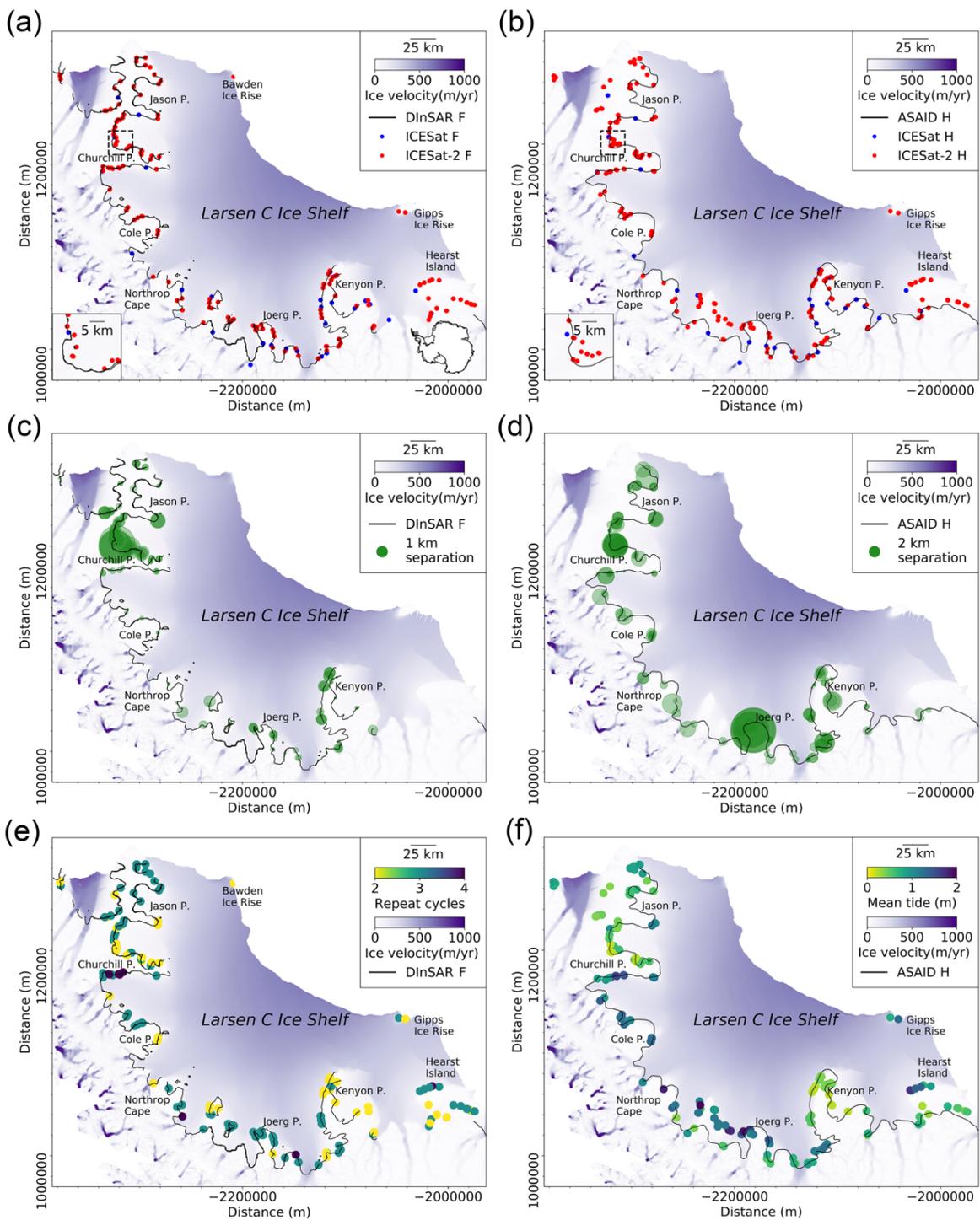
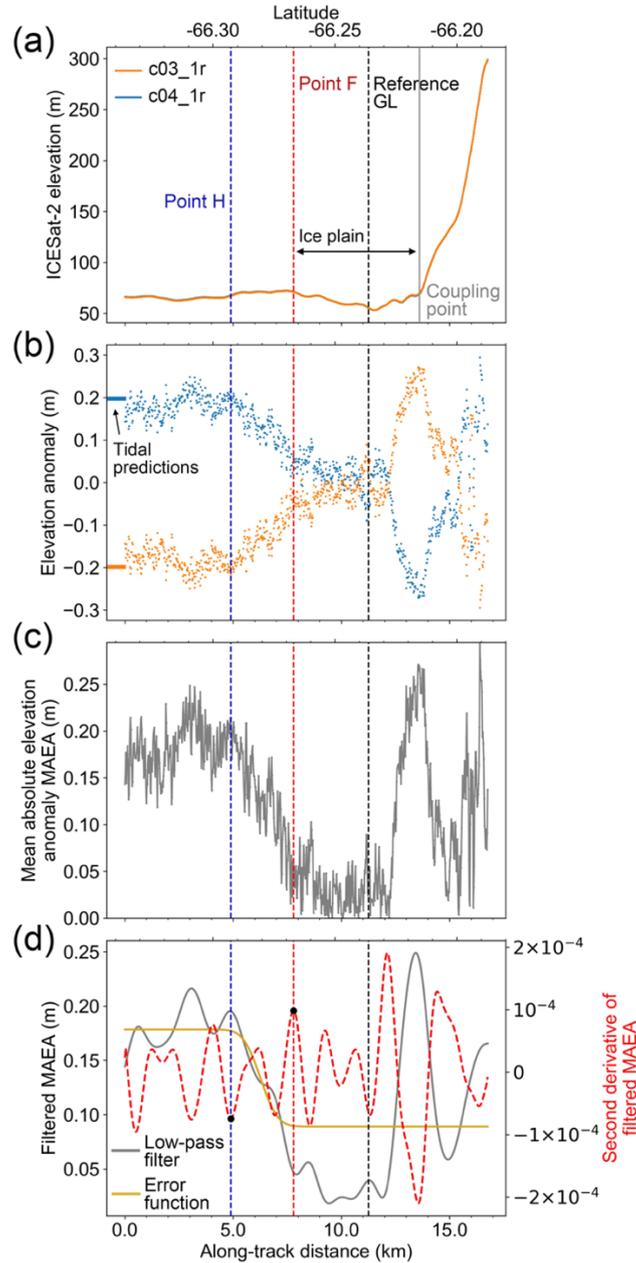


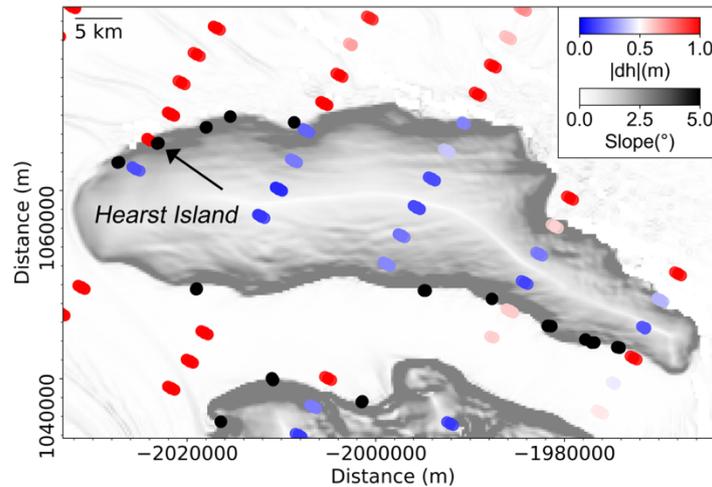
Figure 7. Spatial distributions of ICESat-2-derived GZ features. a) ICESat-2-derived inland limits of tidal flexure (Point F; red dots). For comparison, ICESat-derived Point F (Brunt et al., 2010a) are also shown (blue dots), ESA CCI DInSAR-derived Point F is shown as the black line (ESA Antarctic Ice Sheets CCI, 2017). b) same as a), but showing ICESat-2-derived inland limit of

hydrostatic equilibrium (Point H; red dots) and ICESat-derived Point H (Brunt et al., 2010a) (blue dots), Point H from the ASAIID grounding line project is shown as the black line (Bindschadler et al., 2011). c) Absolute separations between ICESat-2-derived Point F and ESA CCI DInSAR-derived Point F. d) Absolute separations between ICESat-2-derived Point H and ASAIID Point H. e) Number of repeat cycles used to calculate the grounding zone (GZ) features. f) Distribution of mean ocean tide range at Point H. In all subplots, data are superimposed over recent ice surface velocity magnitudes (Rignot et al., 2017) in Antarctic Polar Stereographic (epsg:3031) projection.



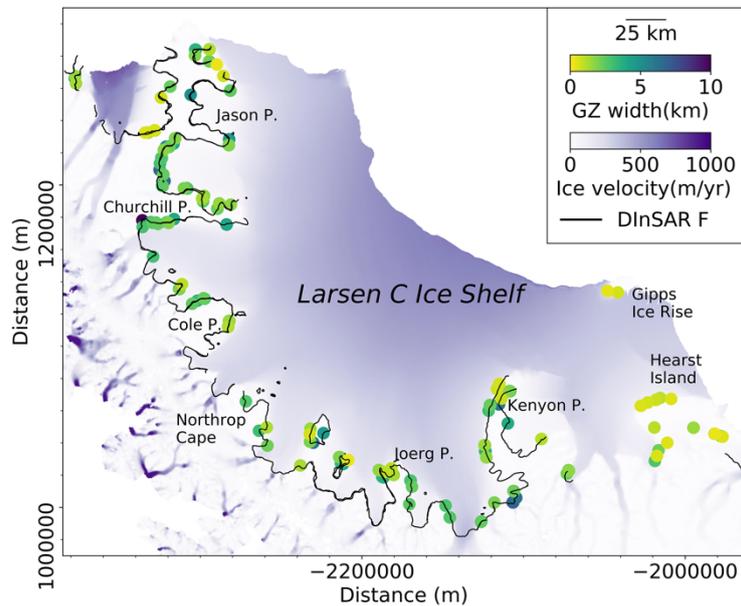
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Figure 8. ICESat-2 repeat track analysis for two right beams from repeat cycles 3 and 4 in beam pair 1 of track 506. The location of track 506 beam pair 1 is shown in Figure 2. Same as Figure 5, but showing the existence of an ice plain between the inland limit of tidal flexure (Point F) and the coupling point.



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Figure 9. Spatial distribution of ICESat-2 crossovers in Hearst Island. The absolute change in elevation at each crossover, $|dh|$, is shown as the color-coded dots. ICESat-2-derived inland limit of tidal flexure (Point F) is shown as black dots. Background is the surface slope from the REMA DEM with a 250 m resolution (Howat et al., 2019) in Antarctic Polar Stereographic (epsg:3031) projection. **Figure 8. Locations of the absolute elevations changes of the crossovers. a) Jason Peninsula and Churchill Peninsula shown in dashed black box A in Figure 6c. b) Kenyon Peninsula shown in dashed black box B in Figure 6c. c) A set of crossovers from three beam pairs of the ascending track 1131 and the descending track 1245 from repeat cycle 1. Background is the surface slope from the REMA DEM with a 250 m resolution (Howat et al. 2019).**



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Figure 10. Distributions of GZ width. ESA CCI DInSAR-derived inland limit of tidal flexure (Point F) is shown as the black line (ESA Antarctic Ice Sheets CCI, 2017). Background is the recent ice surface velocity magnitudes (Rignot et al., 2017) in Antarctic Polar Stereographic (epsg:3031) projection.

685 **Appendix A**

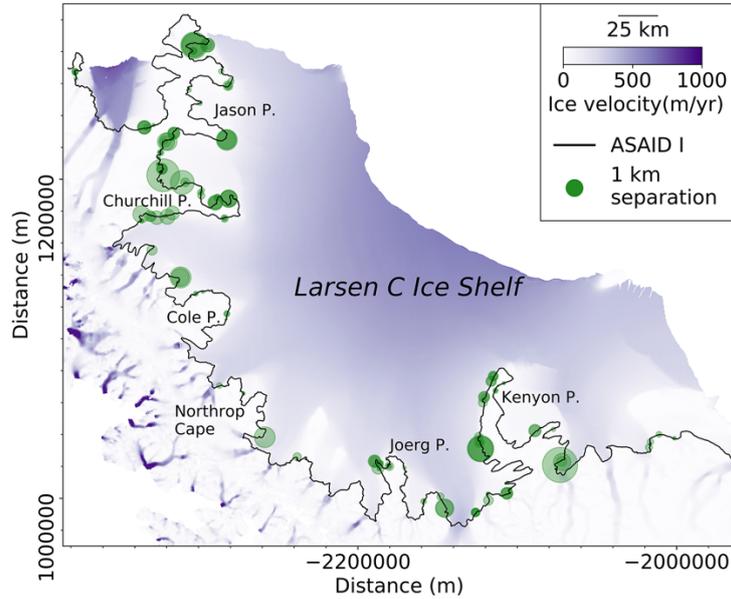


Figure A1. Absolute separations between ICESat-2-derived inland limit of tidal flexure (Point F) and ASAID break-in-slope point (Point I). ASAID Point I is shown as the black line (Bindschadler et al., 2011). Background is the recent ice surface velocity magnitudes (Rignot et al., 2017) in Antarctic Polar Stereographic (epsg:3031) projection.

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