We are grateful to the editor and reviewers for their time and constructive comments to improve this manuscript. Here we address our reply point by point, in bold font. Both editor's and reviewer's comments are in regular font. All changes are marked with red in the revised manuscript.

Editor Decision: Reconsider after major revisions (15 Apr 2016) by Andreas Vieli

Comments to the Author:

Dear X. Wang et al,

Thank you for your substantial revision of your paper and for addressing the comments/concerns of the two reviewers. As the revisions were rather substantial i will send the paper out for review again. However, although the authors have also addressed most of editing and writing (English) issues highlighted by the authors, the revised parts and new text passages clearly suffer again from such editing/writing issues (singular/plural, missing articles, awkward/confusing formulations etc...). I have listed some below (the most obvious) but this list is not exhaustive. So, before I can send the paper out to review again, i ask you to carefully check the whole text again for editing issues and writing etc as we should not expect that the reviewers should do this editing job. I am sure the reviewers will very much appreciate your effort on this. Not that the list below is probably far from complete and there may be more issues that I did not spot when reading through quickly. So although the system may say 'major revision before reconsideration' it actually is rather 'minor' revisions (as easy to do) before sending it to re-review.

Thank you and best regards

Andreas Vieli

The editor

Reply: Thank you for your comments. We have revised the manuscript thoroughly according to your comments.

Some obvious editing/writing issues:

Line 129/130: '…for each of the datasets from Novemeber…'

Reply: Done.

Line 133: should be in plural: 'clouds'

Reply: Done.

Line 137: add ‘the’: ‘…correction from the TPX07.1…’

Reply: Done.

Line 139: ‘under WGS-84 ellipsoid’ seems awkward, maybe ‘…using the WGS-84 ellipsoid …’ or ‘…with the WGS-84 ellipsoid …’ would be better

Reply: We change it to ‘related to the WGS-84 ellipsoid’.

Line 148: i think the word ‘even’ is here rather awkward and is not needed here.

Reply: ‘even’ is deleted.

Line 151: I can not follow ‘…MIT almost repeatedly along the same track…’. Rephrase clearer.

Reply: We change it to ‘ICESat observed the MIT almost repeatedly along different tracks in different campaigns’.

Line 173 and elsewhere: please remove the inverted commas around all the variables in the text (e.g. ‘x’), writing them as italics is enough.

Reply: All the inverted commas around the variable in italics in the text have been removed.

Line 173 to 178: whenever it say something like…‘var1’ and ‘var2’ is… I think you should use the plural for the verb: …‘var1’ and ‘var2’ are… and then the noun later should also be in plural (for example: t1 and t2 are the start and end times.

Reply: All these issues have been corrected in the revision.

Line 183: replace ‘kriging’ by ‘it’

Reply: Done.

Line 203: replace ‘…will be soon introduced…’ by ‘…is introduced…’

Reply: Done.

Line 218: change to ‘…convenient (…) and is defined…’

Reply: Done.

Line 226: delete the second ‘layer’ (‘…of the firn layer on top of an …’)

Reply: Done.

Line 234: simplify to ‘It is critical to target and use icebergs that fulfil these requirements….’

Reply: Done.

Line 249-250: remove: in terms of estimating ….itself.

Reply: Done.

Line 295-296: move the ‘and’ to after ‘Delta_E_krig’

Reply: Done.

Line 308: ‘is relatively correct’??? I do not understand this, do you mean ‘reasonably accurate’?

Reply: We change it to ‘reasonably accurate’.

Line 320/321: ‘the interpolated freeboard’ rather than ‘the freeboard interpolation’? AND ‘in average’

Reply: Done.

Line 349/350: ‘…and outlines of the MIT … are shown…’

Reply: Done.

Line 364: add a comma after ‘Also’. This sentence is as a whole a bit awkward.

Reply: We change it to ‘Also, it would be difficult for the MIT to approach the buffer region (indicated with yellow to red color in Fig. 6) as the surrounding Mertz Bank gets shallower and steeper, suggesting substantive grounding potentials’.

Line 374: ‘as time passed on’ (rather than ‘with passing time’)

Reply: Done.

Line 390: awkward formulation: maybe write ‘…needed to climb more 140m to pass it…’ or ‘ …needed to climb the 140m obstacle to cross it’.

Reply: We change it to ‘the MIT would have needed to climb the 140m obstacle to cross it’.

Line 408: I think this should be Fig. 8 (not Fig 7)

Reply: Done.

Line 442: the ‘70 years’ are in a random place in this sentence, maybe write: ‘Additionally, the 70 year cycles of MIT…. well which make …’

Reply: We change it to 'Additionally, the 70 year cycles of MIT calving coincides with surface ocean condition around Mertz well which makes the explanation much more compelling'.

Line 450: '…are discussed in more depth/detail'

Reply: Done.

Line 456: where does the number -3.35 m come from?

Reply: '-3.35 m' is from the Line 190, Section 3.1. It is derived from all sea level extractions from different tracks in different campaigns.

Line 498-499: awkward formulation, maybe say: 'However, other time dependent modelling results from the Mertz region were close to …..' and delete: 'Our result is smaller'.

Reply: Done.

Line 475: somewhat awkward formulation: 'worked only several times a year..' change.

Reply: We change it to 'Second, because ICESat/GLAS observed only several times a year on repeat tracks and icebergs was rotating slowly, the elevation profile in 2006 and 2008 along the same track T1289 may not come from the same ground surface. '.

Line 476: add a 'the' before 'elevation'.

Reply: Done.

Line 481-482: awkward: maybe say: 'Since the larger freeboard measured in 2006 indicates ….'

Reply: Done.

Line 484: '…reason to select the measurement…'

Reply: Done.

Line 487: '…is critical to the final success…'

Reply: Done.

Line 489: '…along the margin…'

Reply: Done.

Line 492: '…front, for both the east and west flanks, …

Reply: Done.

Line 495: I do not see a white polygon in fig 6, do you mean the light grey dash-dotted line with label 20000125? Clarify and maybe change labels in fig 6 to the years (e.g. 2000).

Reply: We change it to 'Inside of the MIT boundary of 2000, the closer to the dash-dotted polygon (Figs. 6 and 7), the better the accuracy the seafloor DEM.' Figs. 3, 6 and 7 are redrawn in order to make the 2000 boundary consistent with each other.

Line 499-450: awkward formulation: '…but only the poorest accuracy …', rephrase

Reply: We change it to 'However, from Beaman et al. (2011), no uncertainty on the seafloor DEM was systematically provided. Instead, only the poorest accuracy of single or multi-beam bathymetric measurements was available'.

Line 500-502: awkward sentence, rephrase ('…it is not possible to conduct further work on evaluation of the seafloor bathymetry ……is difficult to assess'.

Reply: Done.

Line 504-507: I do not understand these sentences.

Reply: We change it to 'Since Beaman et al. (2011) provided the most accurate seafloor DEM over Mertz according to our best knowledge, seafloor DEM inside of dash-dotted polygon (Fig. 7) is kept and the grounding detection is conducted there (Fig. 6) as well. Additionally, the ice tongue never stopped flowing further into the ocean, where the bathymetry measurements density is good'.

Line 516: 'gradual' (not gradually)

Reply: Done.

Line 544: '…is a/the dominant factor….'

Reply: We change it to 'Also the calving cycle of the MIT explains the observed cycle of sea surface conditions change well, which indicates the calving of the MIT is the dominant factor for sea sea-surface condition change'.

Figure 5: caption of figure: please carefully check and rewrite caption, for example (a) does not show 'freeboard' but profile locations …

Reply: We change it to 'Figure 5. Evaluation of kriging interpolation method over the MIT using freeboard data derived from ICESat/GLAS. (a) shows profile locations of freeboard derived from ICESat/GLAS after relocation over the MIT. Gray dots indicate ICESat/GLAS used for interpolation using kriging method. The blue dashed square indicates the region used to

investigate interpolation accuracy of kriging method, about 7 km×7 km. Inside of the square, freeboard data marked with green dots are used to check the accuracy of freeboard interpolated with kriging. (b) is the freeboard comparison result derived by subtracting krigged freeboard from freeboard derived from ICESat/GLAS. The spatial distribution and the histogram of freeboard difference are shown in the lower left and upper right respectively. The black polygon filled with light blue shows the boundary of MIT on November 14, 2002.'

Caption Fig 7Line 774: 'The grounding sections of the MIT boundary in …'

Reply: Done.

Supplementary figure 1: please check and rewrite caption of this figure very carefully:

Line 3: 'in THE red rectangle…'?

Reply: We change it to 'The embedded figure in the lower left is the zoom in of the red rectangle which shows the positions of iceberg A and B (polygon filled in red) on February 19, 2008 (Fig. 4)'.

Line 4: use date rather than 50th day

Reply: We use 'on February 19, 2008' in the revision.

Line 5: 'Blue polylines show the seafloor contours…'

Reply: Done.

Line 6 onwards: does this all have to go into the bracket? These are several sentences!!!

Reply: The bracket has been removed.

Line 7: 'However, for being able to use the Figures…..'???

Reply: Done.

Line 8: 'geo-registered'

Reply: Done.

Line 10: '…with THE thick gray line…'

Reply: Done.

Line 11: successful (not successfully)

Reply: Done.

Reviewer 1:

This paper uses altimetry and bathymetry data to map changes in the grounded area of the Mertz ice tongue during the early-to-mid 2000s. They use the surface heights of lightly-grounded icebergs to estimate the firn air content for the ice tongue, and use this, geoid-corrected altimetry measurements, and a bathymetry map of the ice shelf, to map the difference between the bottom of the ice shelf, at hydrostatic equilibrium, and the sea bed for different time periods. Areas where these maps show the (hydrostatic) ice bottom below the seabed are treated as grounded. The authors find that the northwest flank of MIT (Mertz Ice Tongue) was grounded during 2002-08, and that the grounding increased between 11/2004 and 12/2006. They propose that the MIT would have calved because of increasing grounding extent even if the tongue had not been hit by an iceberg. The authors also examine the rate of change in the area of MIT, and estimate an interval between subsequent tongue calving events of 70 years.

A quick summary of this review is that this manuscript needs a great deal of editing and extensive revision before it is ready for publication. I have presented some of my thoughts about what needs to be fixed, but the writing is of uneven quality and my comments about the reliability of interpolated data should (in my opinion) lead to substantial changes in the text and figures. With this in mind, I have not gone to the effort of editing the paper in detail, and hope that the authors can do so themselves.

Reply: Thank you for your comments. We have made many revisions to the structure. Please find related changes highlighted in red in the text.

A major problem in this manuscript is the lack of bathymetry data under the MIT. Data are scattered, at varying density, seaward of the ice front, and the bathymetry maps appear to resolve the seaward extent of the Mertz Bank, but under the tongue the maps are entirely based on interpolated values. This makes the maps in figure 5 and the statistics in table 2 hard to believe except at the very edge of MIT where the altimetry and bathymetry more or less coincide. The conclusions of the paper are largely independent of the data everywhere except in the area where the data are credible, which makes me wonder why the authors chose to show the mapped elevation-difference values in the areas for which they have no data. The authors should make a clear distinction between results derived from measurements and results derived from interpolated values, and the relative expected accuracies of each.

Reply: Through further reading the references about GEBCO and ETOPO1 seafloor DEM, we do find there exists a bathymetry data gap under the MIT as the reviewer has pointed out. According to Beaman et al. (2011), the oldest bathymetry data collected along the margin of the MIT was at least from 2000. Thus, the boundary of the MIT in 2000 is used to identify

bathymetry measurement gaps, as is indicated in Fig. 6. We want to use this boundary to identify the different quality of the seafloor DEM data.

As far as we know, there are no other new bathymetry measurements which can be used to verify the region of data gaps. Thus a further validation of the seafloor DEM is not conducted. Luckily, the ice tongue moved further into the ocean from 2000 to 2010 before calving, flowing over seafloor where bathymetry measurements density is good. Furthermore, the grounding detected is all located beyond the 2000 MIT boundary. Thus the analysis of grounding detection near the ice front in 2002, 2004, 2006 and 2008 is convincing. In this revision, the grounding detection result from Fig. 6 (Fig. 5, last version) is unchanged. However, the boundary of MIT in 2000 is now added to separate the seafloor area under the MIT where the seafloor was interpolated from the surrounding area where bathymetry measurements have been made. The statistical result of grounding detection in Table 2 is recalculated accordingly. Detailed discussion on the seafloor DEM is added in a newly added section 6.2.3.

A second problem is that the methods are difficult to interpret, in large part because the report cited as “Wang 2014” is not readily available online, and the paper “Wang et al 2014” appears to describe a method for estimating freeboard change, rather than the absolute freeboard used in the present study. A good deal of the material in this paper is based on a technique in that report, described briefly in section 3.1(126-135). This paper should include a full description of the technique. In particular, it is not clear from the description how the relocation step works or what it is supposed to accomplish, or how the surface slope relates to errors in this relocation (line 241). I would also have liked to see a justification for the kriging interpolation between ICESAT profiles; the grounding features appear to be small compared to the gaps between ICESAT tracks, which makes me suspect that the krigged freeboard values may not provide a good indication of grounding.

Reply: For freeboard production, we did not cite Wang 2014, but Wang et al. 2014, which did show how to use ICESat/GLAS data to produce a freeboard map in 2009 before MIT calving. In the revision, more details on the freeboard production method are given in Section 3.1. Uncertainty of kriging interpolation using ICESat/GLAS data is investigated as well which is about ±1.8 m on average in a new Section 4.1. The uncertainty of kriging interpolation is also considered when calculating the final grounding detection accuracy in Section 4.

The authors should also be clear about the tidal values used in the freeboard study. Are the altimetry values corrected for tides? What is the “lowest sea level” mentioned at 155, and elsewhere? Is it derived from a tide model, or is it the lowest observed sea level? Is the tide model on the ICESAT product used, or is a different tide model used? What are the errors involved in each part of this?

Reply: More details on ICESat/GLAS preprocessing and the method to produce the freeboard map has been given in the revised text. Tide correction of ICESat/GLAS GLA12 from TPX07.1 is removed to obtain the instantaneous sea surface condition. "lowest sea level" in line 155 may be confusing and has been changed to "lowest sea surface height among extracted sea surface height from different tracks and different campaigns, which is -3.35 m". It is derived by comparing all sea surface height derived from different tracks and campaigns from 2003 to 2009, not from a tide model. The lowest sea surface height stands for the lowest sea level around Mertz from 2003 to 2009 and is directly from ICESat/GLAS observation. Sea level lower than -3.35 m may in fact exist over the Mertz region since limited ICESat observation in any year may not catch the lowest one. The influence of sea level -3.35 m used in this study is discussed more in a new Section 6.2.1.

The English in the manuscript needs improvement. A few idioms are used throughout that are confusing or distracting. "Inversed" should be "inverted." "Area-changing rate" should just be "area rate." "Least-square" should be "least-squares." Activities in the current study should be in present tense, citations to the literature should be in past tense.

Reply: These grammatical issues have been resolved. The error or uncorrected expression pointed to by the reviewer has been corrected. More unclear descriptions or grammar misuses have been corrected as indicated in red in the revised text.

The FAC calculation (3.2) has some nice features, but needs to be described in more detail. How is the least-squares inversion carried out? What are the error sources?

Reply: More details about FAC calculation have been given. Please read Section 3.2 and 6.2.2.

160-177- is the extensive discussion of other methods of calculating the FAC germain to this study? This section would be clearer if much of this were omitted.

Reply: The introductory part of Section 3.2 has been revised. One paragraph not related to the FAC calculation much has been removed. Please read the revised Section 3.2.

222-229- this paragraph should be in the introductory part of section 3.2, not after the calculations have been presented.

Reply: In the introductory part of Section 3.2, the principle of FAC has been given. However, we want to use this text to discuss limitations of the FAC as calculated from these selected icebergs. In the revision, this paragraph in question is now moved to Section 6.2.2 as part of a deeper discussion on FAC extraction.

247: Where are the interpolation errors for freeboard and bathymetry?

Reply: The influence of kriging interpolation is discussed in Section 4.1. Also the uncertainty of kriging interpolation is derived and now considered in the final accuracy of grounding detection.

From Beaman et al. (2011), the poorest accuracy of single beam and multi-beam measurements was provided. Thus, we use it directly to evaluate the accuracy of the data in Section 4.1. Because the original bathymetry data product from Beaman et al. (2011) and Fretwell et al. (2013) was not collected and processed by us, it is impossible to evaluate the uncertainty of the products. As far as we know, there is no other new bathymetry measurements that can be used to evaluate the seafloor DEM. Thus, for seafloor DEM, we just use the poorest accuracy to reflect the uncertainty of seafloor DEM. The seafloor DEM is further discussed in a new Section 6.2.3.

254- 50 times the average slope is still a very small number (0.6 degrees). A better estimate of the error due to crevassing would be to directly incorporate the crevasse depth into the calculation- thus, instead of v*slope_error (12 m) the contribution would be closer to 50 m.

Reply: Crevasses are important features on the surface of the MIT. In the middle of the tongue, large crevasses can reach a depth of about 50 m. However, this is an extreme and rare occurrence. Around the ice front, the freeboard is about 30 m, as can be seen from Wang et al. (2014). It is therefore not proper to set the crevasse depth in that area to be as large as 50 m. The freeboard error caused by our approach is reasonable because we want to explore the average contribution to grounding detection from footprint relocation by considering ice velocity uncertainty and average surface slope. In this study, we have already magnified it by 50 times. As we feel this is a reasonable approach for the ice front treatment, we kept our original approach in the revised manuscript.

256-62: Why do we need to consider the freeboard stable (or not stable?) It appears that only static estimates of freeboard are used here (derived from single ICESAT campaigns)- so why does it matter that there would be a change (or not) in the freeboard?

Reply: Greater details about the method for freeboard extraction, relocation and mapping are added in Section 3.1. Because we use all ICESat/GLAS data from 2003 to 2009 to produce freeboard for different years, freeboard changes do matter if freeboard changed greatly. Thus, the uncertainty of freeboard change rate does contribute to the final accuracy of grounding detection.

257 “annual changing rate of freeboard” should be “annual rate of freeboard change” or “freeboard rate”

Reply: Done

273: What is the significance of Edif < 34 m? Based on 263-268, this would indicate "not extremely confidently identified as ungrounded." Wouldn't a better statistic be Edif < -34, or "Extremely confidently identified as ungrounded?"

Reply: After considering the interpolation error, the accuracy for grounding detection is now ± 23 m (± 17 m in last version). We provide statistics for those elevation difference with E_dif less than 46 m (twice the standard deviation) so one can have a better estimate of grounding at the tongue. When using E_dif less than -46 m, the slightly grounded sections will be neglected. We use this value of 46 m to describe all possible grounding regions. Furthermore, the statistics in Table 2 do show results in different intervals from 46 m to less than 0.

280: Again: Do you mean "less than -17 m?"

Reply: We mean "less than 23 m" because in 2002, the minimum of 'E_dif' is larger than "-23 m". In this revision, '17' is changed to '23' because of a revised consideration of the kriging interpolation error.

291-293: Reporting Edif within the tongue is a problem, since the bathymetry is not known there. You might report changes along the margin, but the statistics reported here don't seem to mean anything.

Reply: We actually want to express the 'E_{dif}' for those regions listed in Table 2 only, not all regions under the tongue. These regions with 'E_{dif}' less than 46 m do fall beneath the ice front of the MIT. In this revision, we change it to "From 2002 to 2008, more regions under the MIT have 'E_{dif}' less than 46 m the area of which increased from 8 km^2 to 17 km^2. Additionally, the mean of 'E_{dif}' under the tongue for those having 'E_{dif}' less than 46 m gradually decreases from 28.8 m to 12.3 m, according to which we can conclude that the ice front was grounded more significantly with passing time. "

302 Combine the first two sentences, which form a joint conclusion: ". However," should be ", and that"

Reply: Done.

325 (and elsewhere) "Area-expanding trend" should be "area rate" or "rate of area change"

Reply: Done.

367-78: The significance of this paragraph is not clear. Ice-berg scouring is not discussed elsewhere in the paper, so the scientific question addressed by this paragraph needs more introduction.

Reply: This section is removed.

577- “is used in figure 6”– this appears not to be true.

Reply: Changed it to ‘Fig. 4’

589: “closed’ – should this be “closest?”

Reply: Done.

594: The legend here is not consistent with the caption.

Reply: Legend is changed.

606: It is hard to distinguish the outline from the “grounding part.” The choice of colors (yellow on yellow) is not good.

Reply: This figure is redrawn and yellow lines are not used in this version.

Reviewer 2:

The authors use bathymetric, ICESat, and Landsat data products to estimate the firn air content, depth below sea level, re-grounding locations, and advance rate for the Mertz Ice Tongue from 2002-2008. They find that grounding along the Mertz Bank resulted in slight rotation and rifting of the Mertz Ice Tongue that would have resulted in the ice tongue's eventual collapse in the absence of any additional triggering mechanisms. Further, they suggest that the ice tongue collapse has a periodicity of ~70 years and that this periodicity results in periodic variations in local sea ice formation and bottom water formation. Although the topic of the manuscript is interesting, the limited presentation of the methods and irregular quality of the writing make it difficult to follow. In addition to the major revisions listed below, I recommend that the authors go through the text in detail to check the writing and to make sure that all figures are legible.

Reply: Thanks for your comments. We have thoroughly revised the manuscript. The changes are highlighted in red in the revised text.

1) In the data and methods sections, the authors frequently refer the readers to other publications rather than describe the data processing procedures in detail in the text. I find this to be particularly concerning for the freeboard inversions to estimate ice thickness because small errors in freeboard can lead to large variations in the estimated tongue depths. In order to have confidence in the provided tongue depths, I recommend including more detail on the relocation and interpolation procedures. Similarly, more information regarding the uncertainty of the bathymetry data used to identify grounded regions would be incredibly helpful.

Reply: More details about freeboard map production using all available ICESat/GLAS data from 2003 to 2009 is added in a revised Section 3.1. More discussion is added as well in a new Section 6.2.3.

From Beaman et al. (2011), the poorest accuracy of single beam and multi-beam measurements was provided. Thus, we use it directly to evaluate the accuracy of this data in Section 4. Because the original bathymetry data product from Beaman et al. (2011) and Fretwell et al. (2013) was not collected and processed by us, it is impossible to fully evaluate the uncertainty of the products. The seafloor DEM is further discussed in the new Section 6.2.3.

We do acknowledge that in regions with bathymetry gaps, the quality of seafloor topography is poorer compared to other regions. According to Beaman et al. (2011), the oldest bathymetry data used to produce the seafloor DEM that are already known was at least from 2000. Thus, the boundary of the MIT in 2000 is used to identify bathymetry measurement gaps, as is indicated in Fig. 6. We use this boundary to identify the different quality of the seafloor DEM data since as far as we know, there is no other new bathymetry measurements

that can be achieved to verify the region of data gaps. Luckily, the ice tongue moved further into the ocean from 2000 to 2010, before calving, into regions where bathymetry measurements are good. Furthermore, the grounding we detect is all located beyond the 2000 MIT boundary. Thus the analysis of grounding detection near ice front in 2002, 2004, 2006 and 2008 is convincing.

2) It's really difficult to follow the firn air content approximation. I assume the bed elevations are really well constrained under the targeted icebergs and you are simply iteratively estimating the iceberg depths for gradually decreasing values of the mean iceberg density. The units obtained for the firn air content estimated using this method require explanation. I assume that they represent the difference in iceberg depth assuming a constant ice density and the final ice density estimated through the comparison with the underlying bathymetry since the units are in meters, but this is not presented anywhere. It would be helpful to also present the final density inferred for the firn column so that it is easier to compare your estimates with other observations. The error estimates obtained for firn air content should also be presented in more detail. I am particularly concerned with the assumption that the ICESat tracks capture the thickest portion of each iceberg. I'd be more confident in the firn air content estimates if I was also shown that there are relatively small variations in iceberg freeboard along the ICESat tracks because that would increase confidence that the iceberg grounding location is captured by the ICESat data.

Reply: The method for FAC calculation has been revised in Section 3.2. The seafloor DEM is well controlled by the bathymetry measurements as can be seen from S-Fig. 1. A paragraph on why FAC is used and how it is obtained is provided in Section 3.2. Some text not related so much to FAC calculation has now been removed. Fig. 9 is added to show the spatial distribution of freeboard of icebergs. More details on freeboard measurements from ICESat/GLAS, and the limitation of our method for FAC calculation is discussed in Section 6.2.2. Our estimated FAC around Mertz is compared with published modeling results (from Ligtenberg, 2014) in Section 6.2.2. Calculating the average density directly is beyond the scope of the current manuscript.

3) The addition of the iceberg scour section at the end of the discussion is somewhat out of place with the rest of the manuscript. I suggest removing it entirely.

Reply: This section is removed.

Grounding and Calving Cycle of Mertz Ice Tongue Revealed by Shallow Mertz Bank

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Abstract

A recent study, using remote sensing, provided some evidence that a seafloor shoal influenced the 2010 calving event of the Mertz Ice Tongue (MIT), by partially grounding the MIT several years earlier. In this paper, we start by propos~~e~~ing a method to calculate ~~firn~~ Firn ~~air~~ Air ~~content~~ Content (FAC) around Mertz from seafloor-touching icebergs. Our calculations indicate the FAC around Mertz region as 4.87±1.31 m. We then design an indirect method of using freeboard and sea level data extracted from ICESat/GLAS, FAC, and ~~highly~~ relatively accurate seafloor topography to detect grounding sections of the MIT between 2002 and 2008 and analyze the process of grounding ~~before~~ prior to the calving event. By synthesizing remote sensing data, we point out that the grounding position was ~~just~~ localized northeast of the Mertz ice front close to the Mertz Bank. The grounding outlines of the tongue caused by the Mertz Bank are extracted as well~~, however the length is only limited in several kilometers since late 2002~~. From 2002 to 2008, the grounding area increased and the grounding became more pronounced. Additionally, the ice tongue could not effectively climb over the Mertz Bank in following the upstream ice flow direction and that is why MIT rotated clockwise after late 2002. Furthermore, we demonstrate that the area-increasing trend of the MIT changed little after calving (~36 km^2/a), thus allowing us to use remote sensing to estimate the elapsed time until the MIT can reground on the shoal. This ~~time~~ period is approximately 70 years. The calving of MIT can be ~~repeatable~~ cyclical because of the shallow Mertz Bank location and the flow rate of the tongue. ~~and t~~ The calving cycle of the MIT explains the cycle of sea-surface condition change around the Mertz.

Keywords: Mertz Ice Tongue, ~~Firn~~ firn air content, iceberg grounding, Mertz Bank, ~~iceberg scouring,~~ calving cycle.

1. Introduction

Surface-warming induced calving or disintegration of floating ice has occurred in Antarctica, such as the Larsen B ice shelf (Scambos et al., 2000, 2003; Domack et al., 2005; Shepherd et al., 2003). While surface or sub-surface melting has largely been recognized to contribute to floating ice loss in Antarctica (Depoorter et al., 2013), calving caused by interaction with the seafloor has not been widely considered. The Mertz Ice Tongue (MIT) was reported to have calved in 2010, subsequent to being rammed by a large iceberg, B-9B (Legresy et al. 2010). After the calving, the areal coverage of the Mertz polynya, and sea-ice production and dense, shelf-water formation in the region changed (Kusahara et al. 2011; Tamura et al. 2012). However, the iceberg collision may have only been an apparent cause of the calving as other factors had not been fully considered such as seafloor interactions (Massom et al., 2015; Wang. 2014). By comparing ~~inversed~~ inverted ice thickness to surrounding bathymetry, and combining remote sensing, Massom et al., (2015) considered that the seabed contact may have held the glacier tongue in place to delay calving by ~8 years. The interaction of the MIT ~~and~~ with the seafloor, the exact grounding location of the MIT before calving and how severe the grounding was are still not well-known.

The MIT (66 °S-68 °S, 144 °E-150 °E, Fig. 1) is located in King George V Land, East Antarctica, with an ice tongue extending over 140 km from its grounding line to the tongue front and approximately 30 km wide at the front (Legresy et al., 2004). Much field exploration has been conducted around Mertz and ~~T~~the increasing availability over the last decade of remote sensing, hydrographic surveying, and bathymetric data allow the causes of ice tongue instability to gradually come into focus. From satellite altimetry, a modest elevation change rate of 0.03 m/a (Pritchard et al., 2012) and a freeboard change rate of -0.06 m/a (Wang et al., 2014) were found, which implied that the combined effects of surface accumulation and basal melt were not dramatic for this ice tongue. For the MIT, investigations of tidal effects, surface velocity, rift propagation, and ice front propagation (Berthier et al., 2003; Frezzotti et al., 1998; Legresy et al., 2004; Lescarmontier et al., 2012; Massom et al., 2010, 2015) have been conducted with an objective of detecting underlying factors affecting stability. Grounding as a potential factor can affect the stability of an ice tongue, as recently pointed out by Massom et al. (2015). However, without highly accurate bathymetric data, it is impossible to carry out such study. Fortunately, In 2010, a new and high resolution bathymetry model, for the seafloor surrounding the Mertz, with a resolution of 100 m was released for the Terra Adelie and George V continental margin (Beaman et al., 2011), and incidentally later used to generate the Bedmap-2 (Fretwell et al., 2013). Such accurate data provides an opportunity for better exploring seafloor shoals and their impact on the instability of MIT. In this study, we focus on the grounding event of the MIT from 2002 to 2008. A method for grounding event detection ~~will be~~is proposed and the grounding of the MIT before calving ~~will be~~is investigated. A calving cycle of the MIT caused by grounding is discussed as well.

2. Data

The primary data used to investigate ice tongue grounding in this study are Geoscience Laser Altimeter System (GLAS) data onboard the Ice, Cloud and land Elevation Satellite (ICESat) and the seafloor bathymetry data mentioned above. In this section, ICESat/GLAS and bathymetry data, as well as some preprocessing are introduced.

2.1 ICESat/GLAS

The ~~Ice, Cloud, and Land Elevation Satellite (~~ICESat~~)~~ is the first spacebone laser altimetry satellite orbiting the Earth, lunched by National Aeronautics and Space Administration

(NASA) in 2003 (Zwally et al. 2002) with ~~Geoscience Laser Altimetry System (~~GLAS~~)~~ as the primary payload onboard. ICESat/GLAS was operated in an orbit of ~600 km and had a geographical coverage from 86 °S to 86 °N. ICESat/GLAS usually observed in nadir viewing geometry and employed laser pulses of both 532 nm and 1064 nm to measure the distance from the sensor to the ground (Zwally et al. 2002). On the ground, ICESat/GLAS's footprint covered an area of approximately 70 m in diameter, with ~~two~~ each adjacent footprints spaced by ~170 m. The horizontal location accuracy of the footprint ~~is~~ was about 6 m (Abshire et al. 2005). The accuracy and precision of ICESat/GLAS altimetry data ~~are~~ were 14 cm and 2 cm respectively (Shuman et al. 2006). ICESat/GLAS usually ~~observed~~ made two or three campaigns a year from 2003 to the end of 2009, with each campaign lasting for about one month. With billions of laser footprints received by the telescope, 15 types of data were produced for various scientific applications, named as GLA01, GLA02, … GLA15. In this study, GLA12 data (elevation data for polar ice sheet) covering the Mertz from release 33 during the interval of 2003 to 2009 is used, the spatial distribution of which is shown in Fig. 2.

2.2 Seafloor Topography

Detailed bathymetry maps are fundamental spatial data for marine science studies (Beaman et al., 2003, 2011) and crucially needed in the data-sparse Antarctic coastal region (Massom et al. 2015). Regionally, around Mertz, a large archive of ship track single-beam and multi-beam bathymetry data from 2000 to 2008 were used to generate a high resolution Digital Elevation Model (DEM), the spatial coverage of which can be found in Fig. 2 of Beaman et al. (2011) and bathymetry data coverage over the Mertz region can be found from S-Fig. 1. The DEM product was reported as having a vertical accuracy of about 11.5 m (500 m depth) and horizontal accuracy of about 70 m (500 m depth) in the poorest situation (Beaman et al. 2011).

Around Antarctica, seafloor topography data from Bedmap-2 was produced by Fretwell et al. (2013) which adopted the DEM from Beaman et al. (2011). In this study, Bedmap-2 seafloor topography data covering Mertz is employed to detect the contact between seafloor and the MIT. Because of inconsistent elevation systems for ICESat/GLAS and seafloor topography data, the Earth Gravitational Model 2008 (EGM08) geoid with respect to World Geodetic System 1984 (WGS-84) ellipsoid is taken as reference. Since seafloor topography from Bedmap-2 is referenced to the so-called g104c geoid, an elevation transformation is required and can be implemented through Eq. (1).

$$E_{sf} = E_{seafloor} + gl04c_{to\_wgs84} - EGM2008 \quad (1)$$

where 'E_{sf}' and '$E_{seafloor}$' is the seafloor topography under EGM08 and g104c respectively, '$gl04c_{to\_wgs84}$' is the value needed to convert height relative to gl04c geoid to that under WGS-84, and '*EGM2008*' is the geoid undulation with respect to WGS-84.

3. Methods

3.1 Grounding Detection Method

ICESat/GLAS data has been widely used to determine ice freeboard, or ice thickness, since its launch in 2003 (Kwok et al., 2007; Wang et al., 2011, 2014; Yi et al., 2011; Zwally et al., 2002, 2008). To study ice freeboard, draft, and grounding of the MIT ~~in different years~~through time, ICESat/GLAS GLA12 data from release 33 from 2003 to 2009 are used as mentioned, and the spatial coverage of which can be seen in Fig. 2. The methods we designed for grounding detection of the MIT are now introduced~~ briefly~~. First, assuming a floating ice tongue, based on freeboard data extracted in different observation dates, the ice draft of the MIT is ~~inversed~~inverted. Next, ice bottom elevation is calculated based on the ~~inversed~~ inverted ice draft and the lowest ~~sea~~ sea-surface height. Finally, the ice bottom is compared with seafloor

~~topography~~ bathymetry and ice grounding is detected. The underlying logic for grounding detection is that if the ~~inversed~~ inverted ice bottom is lower than seafloor, we can ~~deny the former assumption and~~ draw a conclusion that the ice tongue is grounded rather than floating.

The method to extract a freeboard map using ICESat/GLAS from multiple ~~-~~campaigns over the MIT was described in Wang et al. (2014). Here, we ~~will not~~ do not revisit it in detail but introduce it schematically. ~~According to Wang et al. (2014), four~~ Four steps ~~were~~ are included in freeboard map production for each of the datasets from November 14, 2002, March 8, 2004, December 27, 2006 and January 31, 2008.~~extraction~~.

The first step ~~was~~ is on data preprocessing, saturation correction, data quality control, and tidal correction removal. The magnitude of the ICESat/GLAS waveform can become saturated because of different gain setting, or the occurrence of clouds. Thus the saturated waveforms with *i_satElevCorr* (i.e. an attribute from GLA12 data record) greater than or equal to 0.50 m are ignored and those with *i_satElevCorr* less than 0.50 m are corrected by adding the correction back (Wang et al. 2012, 2013). Additionally, measurements with *i_reflctUC* greater than or equal to one are ignored. Furthermore, tidal correction from the TPX07.1 tide model in GLA12 data record is removed to ~~get~~ obtain elevation data on the instantaneous sea surface condition. ~~.~~ Finally, elevation data related to the WGS-84 ellipsoid and EGM 08 geoid for ICESat/GLAS from 2003 to 2009 is prepared for subsequent use.

The second step ~~was~~ is to derive sea-level height according to each track and to calculate freeboard for each campaign. Because of tidal variations near the MIT, surface elevations of the MIT can vary as well. To derive sea-level height from ICESat/GLAS and provide a reference for freeboard calculation for different campaigns, ICESat/GLAS data over the MIT within a buffer region (with 10 km as buffer radius of MIT boundary in 2007) are selected and sea-level height

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is determined as the lowest elevation measurement along each track (Wang et al. 2014). Freeboard is then calculated by subtracting the corresponding sea-level height from elevation measurement of the MIT according to different tracks in the same campaign. Thus freeboard data for different campaigns from 2003 to 2009 is obtained.

The third step ~~was~~ is to relocate footprints ~~with~~ using estimated ice velocity. ICESat observed the MIT almost repeatedly along different tracks in different campaigns (Fig. 2). However, observation from only one campaign cannot provide good coverage of the MIT, which drives us to combine all observations from 2003 to 2009 together to produce a freeboard map of MIT. Fig. 2 shows the spatial coverage of ICESat/GLAS from 2003 to 2009 over the Mertz, but the geometric relation between tracks is not correct over the MIT because the tongue was fast moving and observed in different years by the ICESat. The region observed in an earlier campaign would move downstream later (Wang et al. 2014). For example, ICESat collected data from track T31 on March 22, 2003 and T165 (Fig. 2) on November 1, 2003 respectively. Fig. 2 shows the distance between track T165 and T31, ~7.5 km without considering ice flow. However because of the fast moving ice tongue, the distance of their actual ground tracks on the surface of the MIT should be a little larger because T165 is located upstream and observed later. Thus footprints relocation using ice velocity is critical to obtain accurate geometric relations among different tracks. The ice velocity data from Rignot et al. (2011) generated from InSAR data from 2006 to 2010 is used to relocate the footprints of ICESat/GLAS. Thus the correct geospatial relations between observations from different campaigns can be achieved on November 14, 2002, March 8, 2004, December 27, 2006, and January 31, 2008, through Eqs. (2) and (3). The freeboard change with time should be considered as well, but this contribution is neglected because freeboard comparison from crossing tracks showed a slightly decreasing trend of -0.06

m/a on average (Wang et al. 2014). The spatial distribution of freeboard data over the MIT corresponding to November 14, 2002, is shown in Fig. 5(a).

$$X = x + \sum_{i=1}^{n} v_{xi}\Delta t + v_{xm}t_m \qquad (2)$$

$$Y = y + \sum_{i=1}^{n} v_{yi}\Delta t + v_{ym}t_m \qquad (t_m = t_2 - t_1 - n\Delta t) \qquad (3)$$

where *x* and *y* are locations in the X and Y directions from ICESat measurement directly; *X* and *Y* are locations in the X and Y directions after relocation; v_x and v_y are the ice velocities in the X and Y directions respectively; t_1 and t_2 are the start and end times; Δt is the time interval and *n* indicates the largest integer time steps for time interval between t_1 and t_2; t_m is the residual time; In this work, Δt is set as 10 days; v_{xi} and v_{yi} is derived from ice velocity field according to different locations during relocation and may change in different time intervals.

The forth step ~~was~~ is to interpolate the freeboard map using the relocated freeboard data from step three. ~~with~~ Inverse Distance Weighting, Natural Neighbor, Spline and Kriging are most widely used interpolation techniques (Childs. 2004). ~~a k~~Kriging interpolation under spatial analysis toolbox of ArcGIS is selected in this study to produce freeboard maps of the MIT because it can provide an optimal interpolation estimate for a given coordinate location by considering the spatial relationships of a data set. ~~method~~. With this method, freeboard maps of the MIT are produced on November 14, 2002, March 8, 2004, December 27, 2006, and January 31, 2008 ~~respectively~~, because of known ice tongue outlines from Landsat images.

Ice draft is calculated with Eq. (~~2~~4) assuming hydrostatic equilibrium and the lowest sea-surface height (further discussed later in Section 6.2.2) is extracted as well from ICESat/GLAS data from all campaigns covering this region, which was -3.35 m under EGM 08 (WGS-84). ~~In a background of changing tidal~~ For time varying sea-surface heights caused by tides, the minimum ~~sea~~ sea-surface height can allow ice with a given draft to ~~most strongly~~ ground to the seafloor.

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Then, ice bottom elevation is calculated by considering the ice draft and the lowest sea-surface height. To compare the ice bottom with the seafloor, an elevation difference of both is calculated. In this way, a negative value indicates that ice bottom is lower than seafloor, which corresponds to ~~a~~ grounding ~~phenomenon~~.

$$\rho_w D = \rho_i (H_f + D - FAC) \quad (~~2~~4)$$

where ~~'~~D~~'~~ is ice draft, i.e. vertical distance from sea surface to bottom of ice; ~~'~~H_f~~'~~ is freeboard, i.e. vertical distance from sea surface to top of snow; ~~'~~ρ_w~~'~~ and ~~'~~ ρ_i~~'~~ are densities of ocean water and ice, respectively. In this study, ice and sea water density are taken as 915 kg/m^3 and 1024 kg/m^3, respectively (Wang et al., 2014); ~~'~~FAC~~'~~ is the firn air content, the decrease in thickness (in meters) that occurs when the firn column is compressed to the density of glacier ice, ~~the same~~ as ~~what was~~ defined in Holland et al., (2011) and Ligtenberg et al. (2014). The calculation of firn air content around Mertz ~~will be~~ is introduced in Section 3.2. In this ~~paper~~work, we define the elevation of at the underside (bottom) of the tongue as ~~'~~E_{ice_bottom}~~'~~ and ~~it can be~~is calculated by Eq. (~~3~~5). ~~Similarly, the elevation difference of ice tongue bottom and seafloor is defined as 'E_{dif}', which can be calculated by Eq. (4).~~

$$E_{ice\_bottom} = E_{sea\_level} - D \quad (~~3~~5)$$

where ~~'~~E_{ice_bottom}~~'~~ corresponds to elevation of the ice bottom. ~~'~~E_{sea_level}~~'~~ is the lowest ~~sea~~ sea-surface height among extracted sea-surface height from different tracks and different campaigns, which is -3.35 m. Similarly, the elevation difference of ice tongue bottom and seafloor is defined as E_{dif}, which can be calculated by Eq. (6).

$$E_{dif} = E_{ice\_bottom} - E_{sf} \quad (~~4~~6)$$

where ~~'~~E_{dif}~~'~~ is elevation difference by subtracting the seafloor elevation from the ice bottom.

3.2. Firn Air Content Estimation Method

The Antarctic ice sheet is covered by a dry, thick firn layer, which represents an intermediate stage between fresh snow and glacial ice, having a varying density between 350 km/m^3 and 900 km/m^{3}from Antarctic inland to the coast (Van den Broke, 2008). The density of firn layer increases from the surface to the bottom, which usually follows an exponential distribution of depth (Patersen, 1994). Using a combination of regional climate model output and steady-state firn compaction model, Tthe density and depth of the Antarctic firn layer has been modeled (e.g., Van den Broke, 2008) using a combination of regional climate model output and a steady-state firn compaction model). However, for ice thickness inversion, Firn Air Content (FAC) is usually used to make the calculation convenient (Rignot and Jacobs. 2002) and is defined as the decrease in thickness (in meters) that occurs when the firn column is compressed to the density of glacier ice (Holland et al., 2011). Time-dependent Firn Air Content (FAC) was has also been modeled by considering the physical process of the firn layer (e.g., Ligtenberg et al. 2014). For the MIT, there are some in-situ measurements of snow thickness available from Massom et al. (2010) who used a snow layer depth of 1 m to derive the thickness of surrounding multi-year, fast sea ice. However on the surface of the MIT, no in-situ measurements of density and or depth of firn layer are available.

Because of different density and thickness of the firn layer on top of an ice tongue, it is challenging to simulate the density profile of the MIT without in-situ measurements as control points. In this study, we use FAC extracted from adjacent seafloor-touching icebergs to investigate the grounding of the MIT rather than FAC from modeling. MIT may be composed of pure ice, water, air, firn or snow that makes ice mass calculation complicated. However, if assuming a pure ice density only to calculate ice mass, the thickness of MIT must be corrected by FAC. FAC correction to ice thickness can be inferred from surrounding icebergs calving from

MIT using Eq. (4) when knowing ice draft and freeboard assuming hydrostatic equilibrium. Thus it is critical to target and use icebergs fulfilling these requirements to solve Eq. (4), such as slightly grounded icebergs above already known seafloor with observed freeboard.

~~To invert glacial ice thickness from freeboard observation under hydrostatic assumption, one can use a two-layer density model, which consists of an upper firn layer and a lower glacial layer (Luckman et al., 2010). In the upper layer, firn density varies with depth. However, in the lower glacial layer, the density is considered a constant. One can also use FAC to correct the inversed ice thickness assuming hydrostatic equilibrium (Rignot and Jacobs, 2002). In this study, we use FAC extracted from adjacent seafloor-touching icebergs to investigate the grounding of the MIT rather than FAC from modeling.~~

From Smith (2011), icebergs can be divided into three categories based on ~~topography~~ bathymetry and seasonal pack ice distributions: grounded ~~iceberg~~, constrained ~~iceberg~~, and free-drifting icebergs. Without occurrence of pack ice, an iceberg can be free-drifting or grounded. Free-drifting icebergs can move several tens of kilometers per day, such as iceberg A-52 (Smith et al. 2007). Grounded icebergs can be firmly or lightly anchored. Heavily grounded icebergs have firm contact with the seafloor and can be stationary for a long time, such as iceberg B-9B (Massom. 2003). However, slightly grounded icebergs may have little contact with the seafloor and can possibly move slowly under the influence of ocean tide, ocean currents, or winds, but much slower than free-drifting icebergs. The relation of ~~grounding~~ grounded and ice drifting velocity is not well-known. However, from slowly drifting or nearly stationary icebergs in open water, we can determine if an iceberg is grounded.

Because of the heavily grounded iceberg B-9B to the east of the MIT blocking the drifting of pack ice or icebergs from the east, icebergs located between B-9B and the MIT are most likely generated from the Mertz or Ninnis glaciers. We ~~can~~ calculate the FAC from these icebergs and later apply it to grounding event detection of the MIT~~, in terms of estimating the FAC of the MIT itself~~. Around the MIT, the locations of three icebergs (‘A’, ‘B’ and ‘C’) were identified using MODIS and Landsat images in austral summer, 2006 and 2008 and shown in Fig. ~~6~~4. Fortunately, ICESat/GLAS observed these icebergs on February 23, 2006 (54th day of 2006) and February 18, 2008 (49th day of 2008). ~~These~~ This allows us to analyze the behavior of the icebergs three-dimensionally. From Fig. 4a, icebergs ‘A’, ‘B’ and ‘C’ changed position little in about two months (from 28 to 85 day of 2006). Thus we can consider these icebergs slightly grounded. These slightly grounded icebergs may plough the seafloor and leave ridges or grooves. In Pine Island Trough, ridges on the seafloor have been already found with a range of 1 to 2 m, which was believed to be influenced by grounding icebergs drifting with tides (Jakobsson et al. 2011; Woodworth-Lynas et al. 1991). From this viewpoint, we are confident that under the lowest sea level (lowest tide), these iceberg must be grounded, which means that the ice draft ~~inversed~~ inverted from freeboard measurement assuming hydrostatic equilibrium must be greater than or equal to water depth. Based on this analysis, we can take water depth as draft to calculate the FAC~~ and the FAC calculated with this method should be less than or equal to the absolute value~~.

Because only ‘A’ and ‘C’ were observed by track T1289 of the ICESat/GLAS in 2006, freeboard and water depth from bathymetry for both are used to calculate the FAC (Fig. 4, 9 and Table 1). However, the icebergs were not stationary, which indicates only some parts were grounded. In this study, only the top two largest ~~measurements of each~~ freeboard measurements of icebergs 'A' and 'C' from ~~profile~~T1289 in 2006 are employed to calculate the FAC with Eq. (~~2~~7) with a ~~least~~ least-squares method under hydrostatic equilibrium. ~~The result is listed in Table 1.~~

$$FAC = H_{f\_k} + D_k - \frac{\rho_w}{\rho_i} D_k + \varepsilon_k \qquad (7)$$

where k is used to identify different icebergs 'A' or 'C', H_f is the top two largest freeboard measurement of each iceberg, D is ice draft which is the same as sea water depth and is taken from seafloor bathymetry directly, ε is a residual for FAC.

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~~From Table 1, we can find the average~~ Table 1 shows the freeboard and seafloor bathymetry under the icebergs in 2006 for FAC calculation and grounding detection of icebergs in 2008 (detailed freeboard values for these icebergs can be seen from Fig. 9). With freeboard and seafloor measurements from iceberg 'A' and 'C' in 2006 (Table 1), the FAC is calculated as about 4.87±1.31 m. ~~Under this FAC setting, the accuracy of grounding detection with this method is about ±11 m (one standard deviation of the residuals).~~ Two icebergs 'A' and 'B' were observed by the same track T1289 of the ICESat/GLAS on February 18, 2008 and thus are used to evaluate the grounding detection using this FAC ~~result~~. From ~~positions~~ iceberg trajectories observed by remote sensing ~~in~~ (Fig. 4b), we know, iceberg 'A' drifted away from its original position. Thus it was not grounded. However, ~~I~~iceberg 'B' kept rotating in this period without drifting away, from which we can consider it grounded. Such grounding status determined from remote sensing can also be detected with our method since ~~T~~the elevation difference of ice bottom and seafloor ~~is shown in~~from Table 1~~, from which we can see that~~ does clearly indicate a ~~grounding~~ grounded iceberg 'B' and a floating iceberg 'A' ~~is clearly identified~~. Thus, our ~~the~~ FAC estimation works well around Mertz.

~~Actually, for FAC calculation, icebergs just touching the seafloor should be used, in which case, the FAC calculated assuming hydrostatic equilibrium is the same as the actual value. However, it is difficult to ascertain whether an iceberg is just touching the seafloor from remote sensing images. The near stationary or slowly rotating iceberg detected should be grounded more severely than one just touching the seafloor, which results in a calculated FAC theoretically larger than the actual value. Thus using this FAC result to detect grounding can lead to smaller grounding results. However, once an iceberg or ice tongue is detected as grounded, the result should be robust.~~

4. Accuracy ~~Prediction for~~of Grounding Detection

The accuracy of ‘E_{dif}’ is critical to grounding detection of the MIT. From Eq. (1) to (~~4~~6), we ~~can~~ find different components of the error sources, such as ~~errors~~ from sea surface height determination, ice draft, seafloor bathymetry, and elevation transformation. Meanwhile, uncertainty of ice draft is primarily determined by that of freeboard and ‘*FAC*’. Furthermore, the uncertainty of freeboard is influenced by footprint relocation and freeboard changing rates. Considering all mentioned above, the error source of elevation difference ‘E_{dif}’ can be synthesized by Eq. (~~5~~8):

$$\Delta E_{dif} = \Delta E_{sl} + a(\Delta H_f + \Delta E_{re} + \Delta E_{fb_c} + \Delta FAC + \Delta E_{krig}) + \Delta E_{sf} + \Delta E_{trans} \quad (\text{~~5~~}8)$$

where $a = \frac{\rho_i}{\rho_w - \rho_i}$; ‘$\Delta$’ stands for error of each variable; ‘ΔE_{dif}’ stands for error of final elevation difference of ice bottom and seafloor; ‘ΔE_{sl}’, ‘ΔH_f’, ‘ΔE_{re}’, ‘ΔE_{fb_c}’, ‘ΔFAC’, ‘ΔE_{sf}’ ~~and~~, ΔE_{krig}, and ‘ΔE_{trans}’ stand for errors caused by sea surface height extraction, freeboard extraction, freeboard relocation, freeboard changing rates, FAC calculation, seafloor bathymetry, kriging interpolation and elevation system transformation, respectively.

Usually, the influence of elevation system transformation on final elevation difference can be neglected. Based on the error propagation law, the uncertainty of elevation difference E_{dif} can be described by Eq. (9):

$$\varepsilon E_{dif} = \sqrt{(\varepsilon E_{sl})^2 + a^2[(\varepsilon H_f)^2 + (\varepsilon E_{re})^2 + (\varepsilon E_{fb_c})^2 + (\varepsilon FAC)^2 + (\varepsilon E_{krig})^2] + (\varepsilon E_{sf})^2} \quad (9)$$

where ε indicates the uncertainty of each parameter.

4.1 Uncertainty of kriging interpolation

Fig. 5a shows the spatial distribution of freeboard data over the MIT used for detecting grounding on November 14, 2002. The spatial difference of ICESat/GLAS between Fig. 2 and Fig. 5 are caused by footprint relocation, after which the spatial geometry between different tracks is reasonably correct. In the lower right of the Mertz ice front (Fig. 5a), the freeboard distance between track T1289 and T165 is about 7 km. In these data gaps, freeboard data used for grounding detection in Section 3.1 is interpolated using kriging. Thus, knowing the uncertainty of kriging interpolation is critical to final grounding detection.

To investigate interpolation uncertainty of the kriging method, freeboard measurements should be compared with interpolation ones. Thus, a testing region with freeboard measurements is selected, indicated by a blue dashed square in Fig. 5a, about 7 km×7 km. A freeboard map is first interpolated with gray dots only (Fig. 5a) using kriging. Then, the freeboard measurements (284 of green dots in Fig. 5a) are compared with interpolation in the square. The spatial distribution and the histogram of freeboard difference derived by subtracting krigged freeboard from freeboard derived from ICESat/GLAS is shown in Fig. 5b.

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In this square, the freeboard measurement varies from 31.6 m to 40.0 m with 36.6 m in average. However, the interpolated freeboard varies from 32.9 m to 39.6 m with 35.9 m in average. From the freeboard difference results (Fig. 5b), we find that the interpolation results show similar results compared with freeboard derived from ICESat/GLAS. The interpolated freeboard has an accuracy of -0.7 ± 1.8 m. The interpolated freeboard using kriging can reflect the actual freeboard well. Also, the distribution of freeboard difference in Fig. 5b does not show obvious geospatial variation trend.

4.2 Grounding Detection Robustness

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Since sea level is extracted from ICESat/GLAS data track by track, we use ±0.15 m as the uncertainty of elevation data (~~‘~~εE_{sl}~~’~~). Also from Wang et al. (2014), we can see the uncertainty of freeboard extraction (~~‘~~εH_f~~’~~) is ±0.50 m. From Rignot et al. (2011), the error of ice velocity ~~here~~ ranged from 5 m/a to 17 m/a. Assuming that ice velocity varied by 17 m/a (an upper threshold), the relocation error horizontally could reach ±54 m in an average of three years~~’ time~~. Wang et al. (2014) extracted the average slope of the MIT along ice flow direction as 0.00024. However, because of large crevasses on the surface, we use 50 times of this value as a~~n~~ conservative estimate of the average slope. In this way, we can estimate ~~‘~~εE_{re}~~’~~ as ±0.65 m when considering a three-year period. The annual rate of freeboard change ~~annual changing rate of freeboard~~ from 2003 to 2009 is -0.06 m/a (Wang et al. 2014). Therefore, we consider the freeboard stable ~~in~~ over this period. However, when combining data from different time periods then ~~‘~~εE_{fb_c}~~’~~ is estimated as about ±0.18 m if considering three years~~’~~ time difference. From Beaman et al. (2011), considering elevation uncertainty at the worst situation when water depth is 500 m, ~~‘~~εE_{g104c}~~’~~ is ±11.5 m. For kriging interpolation, from analysis in Section 4.1, 1.8 m is taken as the uncertainty. Using all these errors above, we calculate the final uncertainty of elevation difference as ± ~~17~~ 23 m.

From the calculations above, we can say that ~~'~~E_{dif}~~'~~ less than ~~-17~~23 m corresponds to a very robust grounding event. However, if the ~~'~~E_{dif}~~'~~ is greater than ~~17~~ 23 m, we can not confirm ~~no~~ grounding ~~there~~. ~~'~~E_{dif}~~'~~ in the interval of -~~17m~~ 23m to ~~17~~ 23 m corresponds to slight grounding or floating. We can also determine different contributions of each separate factor to the overall accuracy. Seafloor bathymetry contributes the largest part and is the dominant factor affecting the accuracy of grounding detection.

5. Grounding Detection Results

The spatial distribution of elevation difference ~~'~~E_{dif}~~'~~ and outlines of the MIT from 2002 to 2008 ~~can be found~~are shown in Fig. ~~5~~6. A buffer region with ~~buffer~~ radius of 2 km (region between black and grey lines in Fig. ~~5~~6) is ~~also~~ introduced to investigate grounding potential of the MIT, if it approached there. The elevation difference less than ~~34~~ 46 m (twice of elevation difference uncertainty ~~'~~εE_{dif}~~'~~) both inside and outside of the outline is extracted and the corresponding statistics are shown in Table 2. Since the uncertainty to determine a grounding event is about ± ~~17m~~23m, if some grid points of the MIT have elevation difference ~~'~~E_{dif}~~'~~ less than ~~17~~ 23 m, we can conclude that this section of the tongue is almost grounded. The smaller the ~~'~~E_{dif}~~'~~, the more robust the grounding. From the color-change patterns of Fig. ~~5a~~6a-d, we can see that part of the ice front grounded on the shallow Mertz Bank from the end of 2002.

As illustrated from Table 2, the minimum~~'~~E_{dif}~~'~~ inside of the MIT are all less than ~~17~~ 23 m and the mean and minimum of the ~~'~~E_{dif}~~'~~ in the buffer region are all less than 0 from 2002 to 2008. From this, we ~~can~~ conclude that the ice tongue has grounded on the shallow Mertz Bank since November 14, 2002. This result coincides with findings from Massom et al. (2015) who considered that the northwestern extremity of the MIT started to contact with the seafloor shoal in late 2002 to early 2003. Also, it would be ~~hard~~ difficult for the MIT to approach the buffer region (indicated with yellow to red color in Fig. ~~5~~6) as the surrounding Mertz Bank gets shallower and steeper ~~and~~, suggesting substantive grounding potentials ~~would happen if it moved into these regions~~. Inside of the MIT, the minimum of elevation difference was just 11.9 m on November 14, 2002, which indicates little to no grounding. However on March 8, 2004, December 27, 2006, and January 31, 2008, the minimum of elevation difference reached -46.0 m, -52.3 m and -34.8m respectively, which means significant grounding occurred in some regions. From 2002 to 2008, more regions under the MIT have E_{dif} less than 46 m, the area of which increased from 8 km^2 to 17 km^2. Additionally, the mean of ~~'~~E_{dif}~~'~~ ~~inside~~ under of the tongue for those having E_{dif} less than 46 m gradually decreases from ~~25.0~~28.8 m to 12.3 ~~0.8~~m, according to which we can conclude that the ice front was grounded more significantly ~~with passing~~as time passed on. Additionally, since the grounding area increased from ~~6~~ 8 km^2 to ~~13~~ 17 km^2 (Table 2) and the mean of ~~'~~E_{dif}~~'~~ decreased from 2002 to 2008, we can say that over the period from 2002 to 2008, the grounding of the northwest flank of the MIT became more widespread.

Based on the calculated elevation difference, the grounding outlines of the MIT are delineated ~~on~~ for November 14, 2002, March 8, 2004, December 27, 2006 and January 31, 2008, ~~respectively~~ (Fig. ~~6~~7). For the grounding part of the outline in different years, starting and ending location and perimeter are also extracted, from which we can conclude that the length of the grounding outline ~~because~~ of the Mertz Bank is only limited to a few kilometers (Table 3).

We find that the lower right (northwest) of the MIT was always grounded and that~~. However,~~ grounding did not occur in other regions (Fig. ~~5~~6). The shallowest seafloor elevation the ice front touched was ~ -290 m in November 2002. In 2004, 2006, and 2008, the lower right

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(northwest) of the MIT even approached the contour of –220 m. Fig. ~~6~~ 7 also shows the extension line of west flank in November, 2002, from which we can see that if the ice tongue moved along the former direction, the ice flow would be seriously blocked when approaching the Mertz Bank. The shallowest region of the Mertz Bank ~~ahead~~ has an elevation of about -140 m and the MIT would have needed to climb ~~over~~ the 140 m obstacle to cross ~~past~~ it. The shallow Mertz Bank would have caused grounding during the climbing. This special feature of seafloor shoal facing the MIT can further explain why the ice velocity differed along the east and west flanks of the MIT before calving and why the ice tongue moved clockwise to the east, as pointed out by Massom et al. (2015). However, because of sparsely-distributed bathymetry data (point measurements) in Mertz region used in Massom et al. (2015), this effect could not be easily seen. Here, from our grounding detection results and surrounding high-accuracy bathymetry data, this effect is more clearly observed.

6. Discussion

6.1 Area Changing Rate and ~70-year Calving Cycle of MIT

Using Landsat TM/ETM+ images from 1989 to 2013, outlines of the MIT are extracted manually. Assuming a fixed grounding line position over this period, the area of the MIT over this period is calculated. Using these data, from 1989 to 2007, an ~~area~~ increasing area rate~~trend~~ of the MIT is shown (from 5453 km^2 to 6126 km^2) in Fig. ~~7~~8. However, the area of the MIT was almost constant from 2007 to 2010, before calving. The largest area of the MIT was 6113 km^2 closest to the calving event in 2010. After the calving, the area decreased to 3617 km^2 in November 2010.

The rate of area change ~~expanding trend~~ for the MIT from 1989 to 2007 is also obtained using a least-squares method, ~~giving a value of~~corresponding to 35.3 km^2/a. However, after the calving a slight higher area-increasing trend of 36.9 km^2/a, is found (Fig. ~~7~~8). On average, the area-increasing rate of the MIT was 36 km^2/a.

The surface behavior such as ice flow direction changes and middle rift changes caused by grounding was analyzed by Massom et al. (2015). In the history of the MIT, one or two large calving events were suspected to have happened between 1912 and 1956 (Frezzotti et al., 1998) and we consider it likely to be only once because of the influence of the shallow Mertz Bank. When the ice tongue touched the bank, the bank started to affect the stability of the tongue by bending the ice tongue clockwise to the east, as can be seen from velocity changes from Massom et al. (2015). With continuous momentum and flux input from upstream, a large rift from the west flank of the tongue would ultimately have to occur and could potentially calve the tongue. A sudden length shortening of the tongue can be caused by such ice tongue calving as indeed had happened in February, 2010. We also consider that even without a sudden collision of iceberg B-9B in 2010, the ice tongue would eventually calve because of existence of the shallow Mertz Bank.

If we take 6127 km^2 as the maximum area of the MIT, assuming a constant area-changing rate of about 36.9 km^2/a after 2010, it will take about 68 years to calve again. When assuming an area changing rate of about 35.3 km^2/a as before 2010, it will take a little longer, about 71 years. Therefore, without considering accidental event such as collision with other large icebergs, the MIT is predicted to calve again in ~70 years. Because of the continuous ice flow upstream, the special location and relatively lower depth of the Mertz Bank, the calving is likely repeatable and a cycle therefore ~~does~~ exists.

After the MIT calved in February, 2010, Mertz polynya size, ~~sea~~ sea-ice production, sea-ice coverage and high-salinity shelf water formation changed. A ~~sea~~ sea-ice production decrease of about 14-20% was found by Tamura et al. (2012) using satellite data and high-salinity shelf water export was reported to reduce up to 23% using a state-of-the-art ice-ocean model (Kusahara et al. 2010). Recently, Campagne et al. (2015) pointed out a ~70-year cycle of surface ocean condition and high-salinity shelf water production around Mertz through analyzing reconstructed sea ice and ocean data over the last 250 years. They also mentioned that this cycle was closely related to presence and activity of Mertz polynya. However, the reason for this cycle was not fully understood.

From these findings addressed above and MIT calving cycle we found, our explanation is that the calving cycle of the MIT leads to the ~70-year cycle of surface ocean condition and high-salinity shelf water production around Mertz. Calving decreases the length of the MIT suddenly. Then, ~~A~~a short ice tongue reduces the size of Mertz Polynya formed by Antarctic katabatic winds~~ and~~, ~~results~~ resulting in lower ~~sea~~ sea-ice production and further lessens high-salinity shelf water production. Therefore, the cycle of ocean conditions around Mertz found by Campagne et al. (2015) is likely dominated by the calving of the MIT. Additionally, the 70 year cycles of MIT calving coincides with ~~and~~ surface ocean condition change around Mertz ~~coincides with each other~~ well~~, ~70 years,~~ which makes the explanation much ~~exact~~more compelling.

6.2 Key issues influencing grounding detection

Several issues on grounding detection require further clarification, such as sea surface height, FAC value and accuracy of seafloor DEM. In this section, their influences on final grounding detection results are more deeply discussed.

6.2.1 The Lowest Sea-Level Extraction

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In Section 3.1, the lowest sea level -3.35 m is derived by comparing all sea-surface heights derived from different tracks and campaigns from 2003 to 2009. This constant stands for the lowest sea level from results around Mertz from 2003 to 2009 and is directly from ICESat/GLAS observation. However, because of limited observations in each year, ICESat/GLAS may not catch the lowest one. Sea level lower than -3.35 m may exist over Mertz region which would make the grounding results more severe with occurance of more negative values in Fig. 6.

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6.2.2 Firn Air Content Calculation

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FAC varies across the Antarctica ice sheet, usually decreasing from the interior to the coast. In Section 3.2, FAC over Mertz region is derived as 4.87±1.31 m. However other time dependent modeling results from the Mertz region were closed to 5-10 meters (Ligtenberg et al. 2014). Since there are no in-situ measurements available for verification, further comparison work needs to be conducted. However, this FAC value is derived according to our best knowledge over Mertz and is affected by iceberg status (using our approach) and the maximum freeboard used.

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First, for FAC calculation, icebergs just touching the seafloor should be used in which case the FAC calculated assuming hydrostatic equilibrium is the same as the actual value. However, it is difficult to ascertain whether an iceberg is just touching the seafloor from remote sensing images. The near stationary or slowly rotating iceberg detected with remote sensing should be grounded more severely than just touching the seafloor, which may result in a calculated FAC theoretically larger than the actual value. Thus, using this FAC result to detect grounding can potentially lead to smaller grounding results. However, once an iceberg or ice tongue is detected as grounded, the result is more convincing.

Second, because ICESat/GLAS observed only several times a year on repeat tracks and icebergs was rotating slowly, the elevation profile in 2006 and 2008 along the same track T1289 may not come from the same ground surface. Fig. 9 shows the freeboard over iceberg 'A', 'B' and 'C' derived from ICESat/GLAS from 2006 and 2008. By comparing freeboard of iceberg 'A' in 2006 (Fig. 9a), and 2008 (Fig. 9c), we can find that the maximum freeboard was larger and the freeboard profile was longer in 2006. Comparatively, the smaller freeboard in 2008 may be caused by ice basal melting or observing different portion of iceberg 'A'. Since the larger freeboard measured in 2006 indicates a high possibility of capturing the thickest portion, the freeboard measurement in 2006 is used to invert the FAC. Additionally, iceberg 'A' and 'C' did show the similar maximum freeboard (Table 1), which is another important reason to select the measurement in 2006 to invert.

6.2.3 Seafloor DEM

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High accuracy seafloor elevation is critical to the final success of grounding detection. As can be seen from S-Fig.1, there is no bathymetry data under the MIT, which may result in large uncertainty for seafloor interpolation. The oldest bathymetry data collected along the margin of the MIT was at least from 2000 (Beaman et al. 2011). Thus, the boundary of the MIT in 2000 is used to identify bathymetry measurement gaps, as is indicated in Fig. 6. But around the Mertz ice front, for both the east and west flanks, bathymetry data does exist, which provides control points for seafloor interpolation under the tongue. Since the ice front has a width of ~34 km (Wang et al. 2014), the accuracy of seafloor DEM under the MIT varies according to different distances to the control points. Inside of the MIT boundary of 2000, the closer to the dash-dotted polygon (Figs. 6 and 7), the better the accuracy the seafloor DEM. Outside of that boundary, the quality of the

Formatted: Indent: First line: 0.5" seafloor DEM data is much better because of the high density of single-beam or multi-beam bathymetry measurements.

However, from Beaman et al. (2011), no uncertainty on the seafloor DEM was systematically provided. Instead, only the poorest accuracy of single or multi-beam bathymetric measurements was available. Since no new bathymetry data is publicly available in this region, it is not possible to conduct further work on evaluation of the seafloor bathymetry and interpolation error from kriging using bathymetry data is difficult to assess. Thus, the accuracy under poorest situation for bathymetry data is used, the same as used in Beaman et al. (2011).

Since Beaman et al. (2011) provided the most accurate seafloor DEM over Mertz according to our best knowledge, seafloor DEM inside of dash-dotted polygon (Fig. 7) is kept and the grounding detection is conducted there (Fig. 6) as well. Additionally, the ice tongue never stopped flowing further into the ocean, where the bathymetry measurements density is good. From results shown in Fig. 6 all grounding sections of MIT boundary are located outside of the 2000 boundary. Thus the analysis of grounding detection near ice front in 2002, 2004, 2006, and 2008 is convincing. Inside of the 2000 boundary, most of the grounding detection results are above 100 m, indicating a floating status of the corresponding ice. Only abnormal seafloor features higher than this seafloor DEM by about 100 m can result in wide grounding inside. Additionally, from surface features of the MIT from Landsat TM/ETM+ images, no abrupt sunlight shadow related to grounding is detected from 1989 to 2010 near the front, which indicates that the judgment of floating ice tongue inside of the 2000 boundary from Fig. 6 is correct. Actually, no matter whether the MIT inside of the 2000 boundary was grounded or not, gradual grounding on the shallow Mertz Bank of the MIT since late 2002 is a fact, which is direct evidence for us to infer the primary cause of the instability of the MIT.

~~6.2 Iceberg Scouring Detection~~

~~Icebergs play an important role in sediment transport and distribution. Also grounded iceberg can scour the seafloor and disturb the benthic communities on parts of the Antarctic continental shelf. Iceberg scouring across the George V shelf was detected by Post et al. (2011). A recent marine science voyage to the Mertz glacier region was conducted onboard the Australian Antarctic research vessel Aurora Australis in 2011 and one objective of this voyage was to investigate benthic community composition in iceberg scours (Smith and Riddle. 2011). A camera station was set around the Mertz Bank in an attempt to detect iceberg scours caused by the MIT. However, the photos collected from this station indicated no scours. The grounding of the Mertz ice front on the Mertz Bank can leave scours but the camera station was far from grounding regions of the ice tongue by several kilometers. Since the tongue did not move across that place, it is unlikely to find recent scours. We suggest possible new scours detection along the margin of the grounding ice tongue as indicated with thick lines in Fig. 6.~~

7. Conclusion

In this study, a method of FAC calculation from seafloor-touching icebergs around Mertz region ~~was~~ is presented as an important element of understanding MIT grounding. The FAC around the Mertz is about 4.87±1.31 m. This FAC is used to calculate ice draft based on sea level and freeboard extracted from ICESat/GLAS and appears to work well. A method to extract grounding sections of the MIT ~~was~~ is described based on comparing inver~~s~~ted ice draft assuming hydrostatic equilibrium with seafloor bathymetry. The final grounding results explain the surface behavior of the MIT. Previous work by Massom et al. (2015) has also provided some evidence for seafloor interaction, in showing that the MIT front had an approximate 280 m draft with the nearby seafloor as shallow as 285 m, suggesting the possibility of grounding. In our work, we have provided ample detailed bathymetry and ice draft calculations. Specifically, ice bottom elevation ~~was~~ is ~~inversed~~ inverted using ICESat/GLAS data and compared with seafloor bathymetry during 2002, 2004, 2006, and 2008. From those calculations we show conclusively that the MIT was indeed grounded along a specific portion of its northwest flank over a limited region. We also point~~ed~~ out that even without collision by iceberg B-9B in early 2010 the ice tongue would eventually have calved because of momentum and flux input from the upstream glacier flow being increasingly opposed by a reaction force from the shoal of the Mertz Bank.

From remote sensing images we ~~were~~ are able to quantify the rate of increase of area of the MIT before and after the 2010 calving. While the area-increasing trend of the MIT after calving is slightly larger than before, we use~~d~~ the averaged rate to estimate a timescale required for the MIT to re-advance to the area of the shoaling bathymetry from its retreated, calved position. Our estimate is ~70-years, which is remarkably consistent with Campagne et al. (2015) who found a similar period of sea surface changes using seafloor sediment data. A novel point we bring out in our study is that it is the shoaling of the seafloor combined with the rate of advance of the MIT that leads to the 70-year repeat cycle. Also the calving cycle of the MIT explains the observed cycle of sea surface conditions change well, which indicates the calving of the MIT is the dominant factor for ~~sea~~ sea-surface condition change. Understanding the mechanism underlying the periodicity of MIT calving is important as the presence or absence of the MIT has a profound impact on sea ice and hence of bottom water formation in the local region.

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Figures

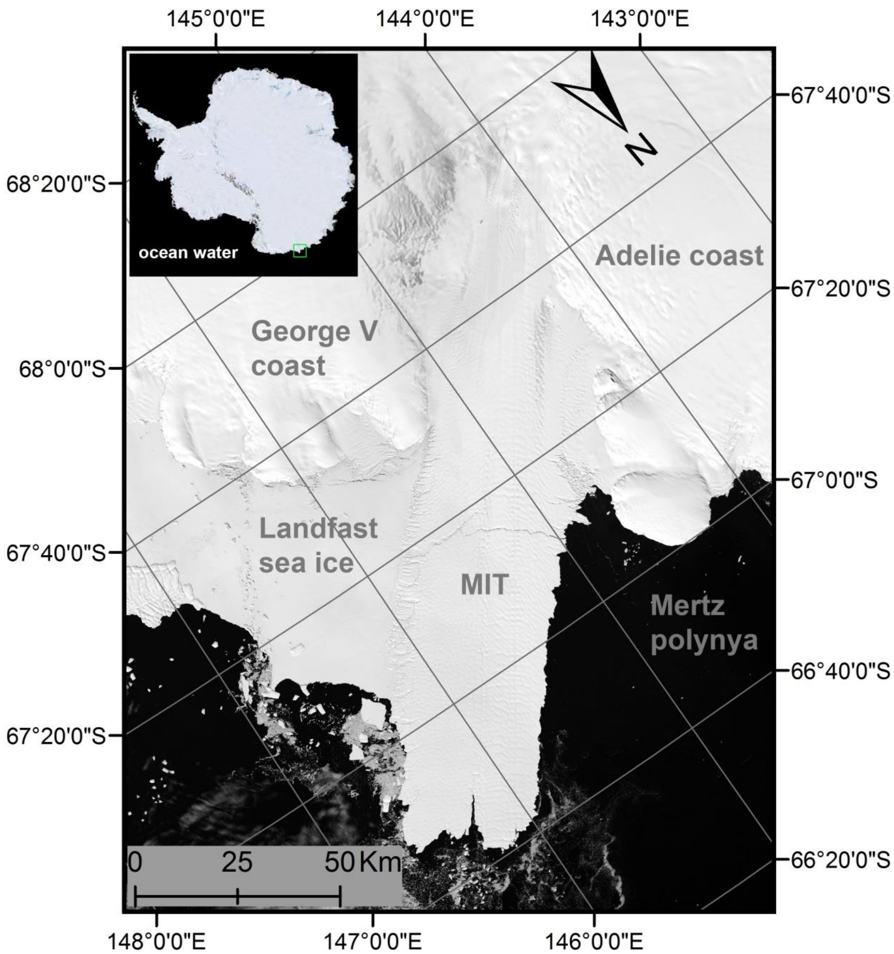
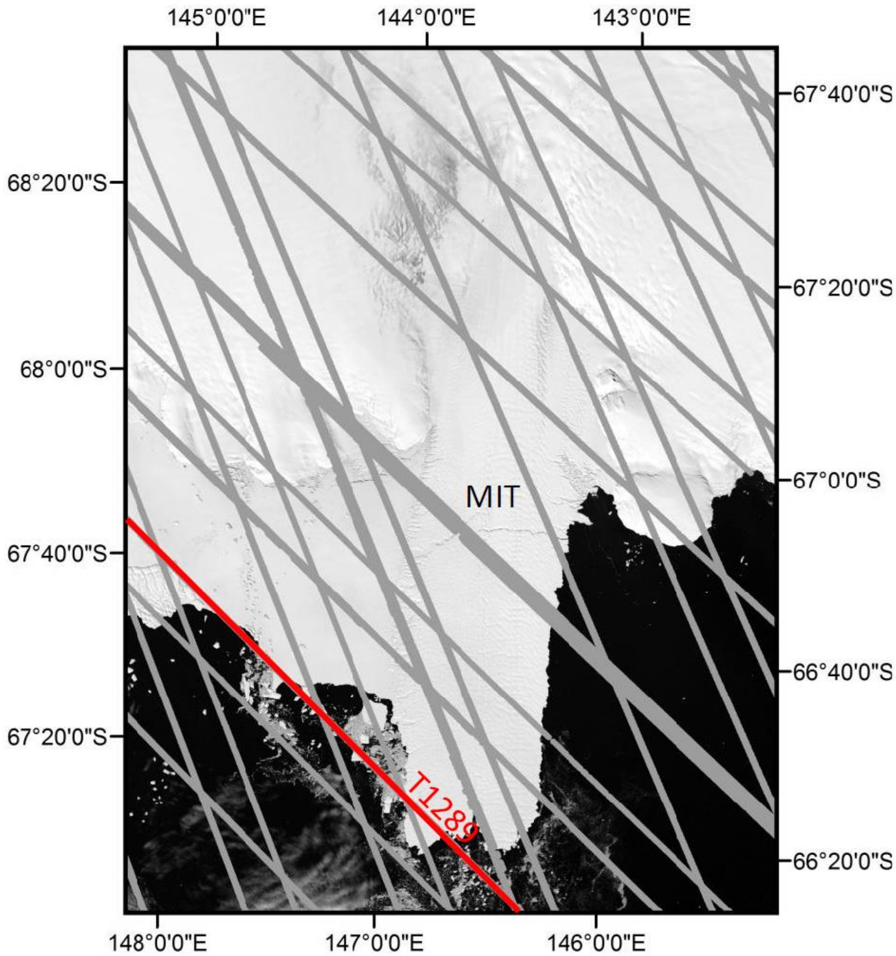


Figure 1. Mertz Ice Tongue (MIT), East Antarctica. Landfast sea ice is attached to the east flank of the MIT and the Mertz Polynya is to the west. The background image is from band 4 Landsat 7, captured on February 2, 2003. The green square found in the upper left inset indicates the location of the MIT in East Antarctica. A polar stereographic projection with -71 °S as standard latitude is used.



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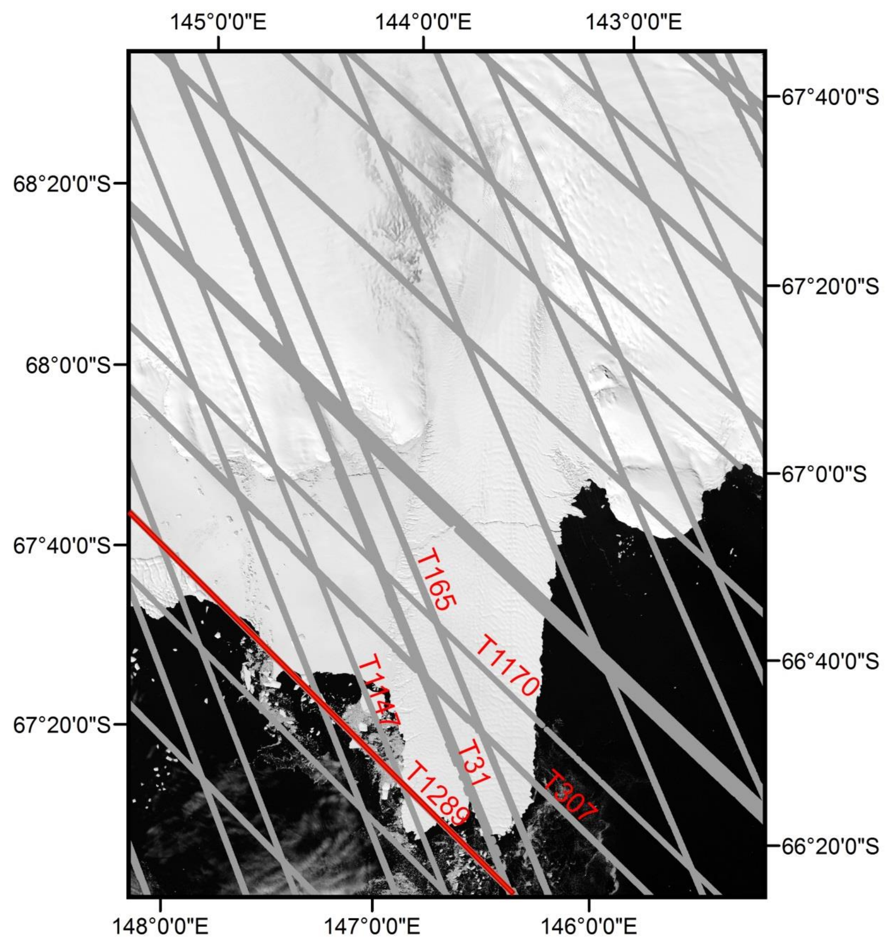
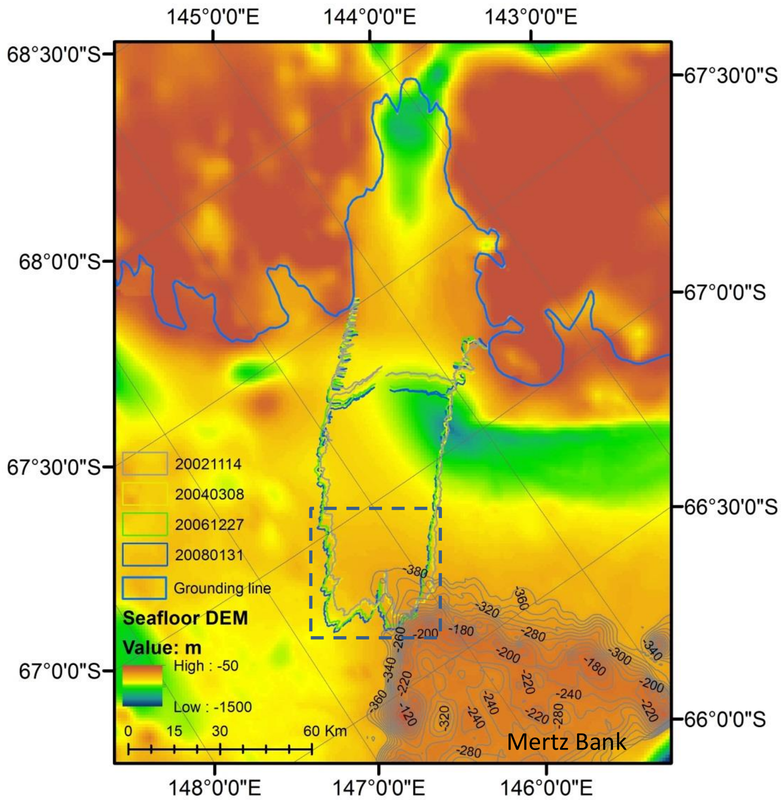


Figure 2. Spatial distribution of ICESat/GLAS data from 2003 to 2009 covering the Mertz region. Ground tracks of ICESat/GLAS are indicated with gray lines. Track 1289 (T1289) is highlighted in red as is used in ~~Figure~~ Fig. ~~6~~4. The background image is from band 4 Landsat 7, captured on February 2, 2003. A polar stereographic projection with -71 °S as standard latitude is used.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Grounding line
Seafloor DEM
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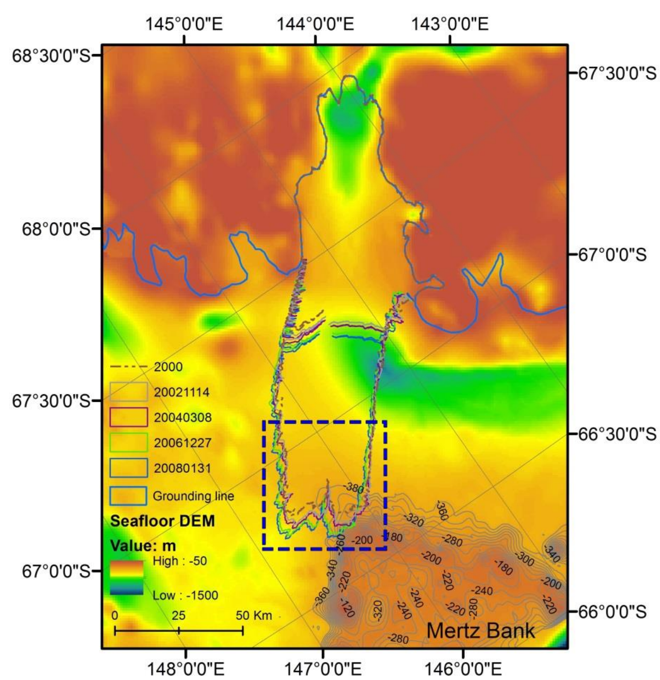
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Figure 3. Seafloor topography from bathymetry around Mertz region and outlines of the MIT from 2002 to 2008. The outlines of the MIT in different years are marked with different colored polygons. The dash-dotted line indicates the shape of the MIT on January 25, 2000, which is used to identify the bathymetry gap under the ice tongue. The shallow Mertz Bank is located in the lower right (northeast). The dash-dotteded blue inset box corresponds to location of ~~Figure~~ Fig, ~~4~~6 and 7. The bathymetry measurement profile can be found from S-~~Figure~~ Fig. 1.

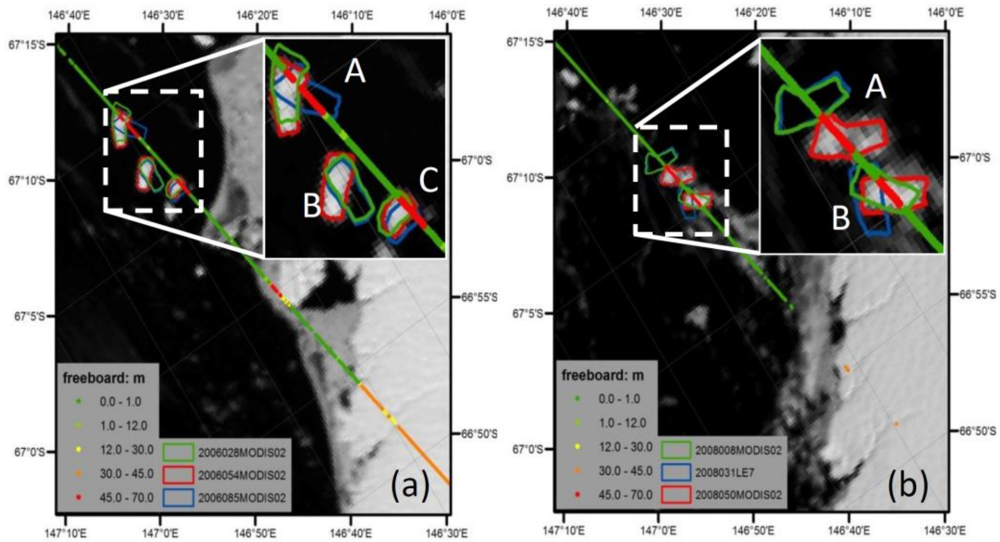
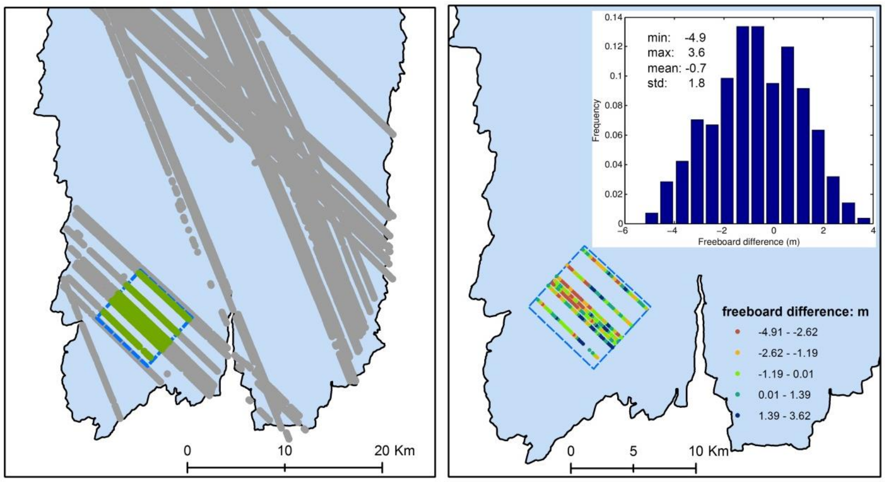


Figure 4. **Iceberg** ~~F~~freeboard extracted from Track 1289, ICESat/GLAS, the location of which can be found in ~~Figure~~ Fig. 2 and S-~~Figure~~ Fig. 1. (a) and (b) show the freeboard extracted from ICESat/GLAS on February 23, 2006 (2006054) and February 18, 2008 (2008049) respectively. In each image, positions of three icebergs (with name labeled as 'A', 'B' and 'C') ~~closed~~ closest to ICESat/GLAS observation time are plotted with green, red and blue polygons respectively. The dates are indicated with seven numbers (yyyyddd) in legend. 'yyyyddd' stands for day 'ddd' in year 'yyyy'. 'MODIS02' and 'LE7' indicate that the image used to extract iceberg outline is from MODIS and Landsat 7 ETM+, respectively.



(a) (b)

Figure 5. Evaluation of kriging interpolation method over the MIT using freeboard data derived from ICESat/GLAS. (a) shows profile locations of freeboard derived from ICESat/GLAS after relocation over the MIT. Gray dots indicate ICESat/GLAS used for interpolation using kriging method. The blue dashed square indicates the region used to investigate interpolation accuracy of kriging method, about 7 km×7 km. Inside of the square, freeboard data marked with green dots are used to check the accuracy of freeboard interpolated with kriging. (b) is the freeboard comparison result derived by subtracting krigged freeboard from freeboard derived from ICESat/GLAS. The spatial distribution and the histogram of freeboard difference are shown in the lower left and upper right respectively. The black polygon filled with light blue shows the boundary of MIT on November 14, 2002.

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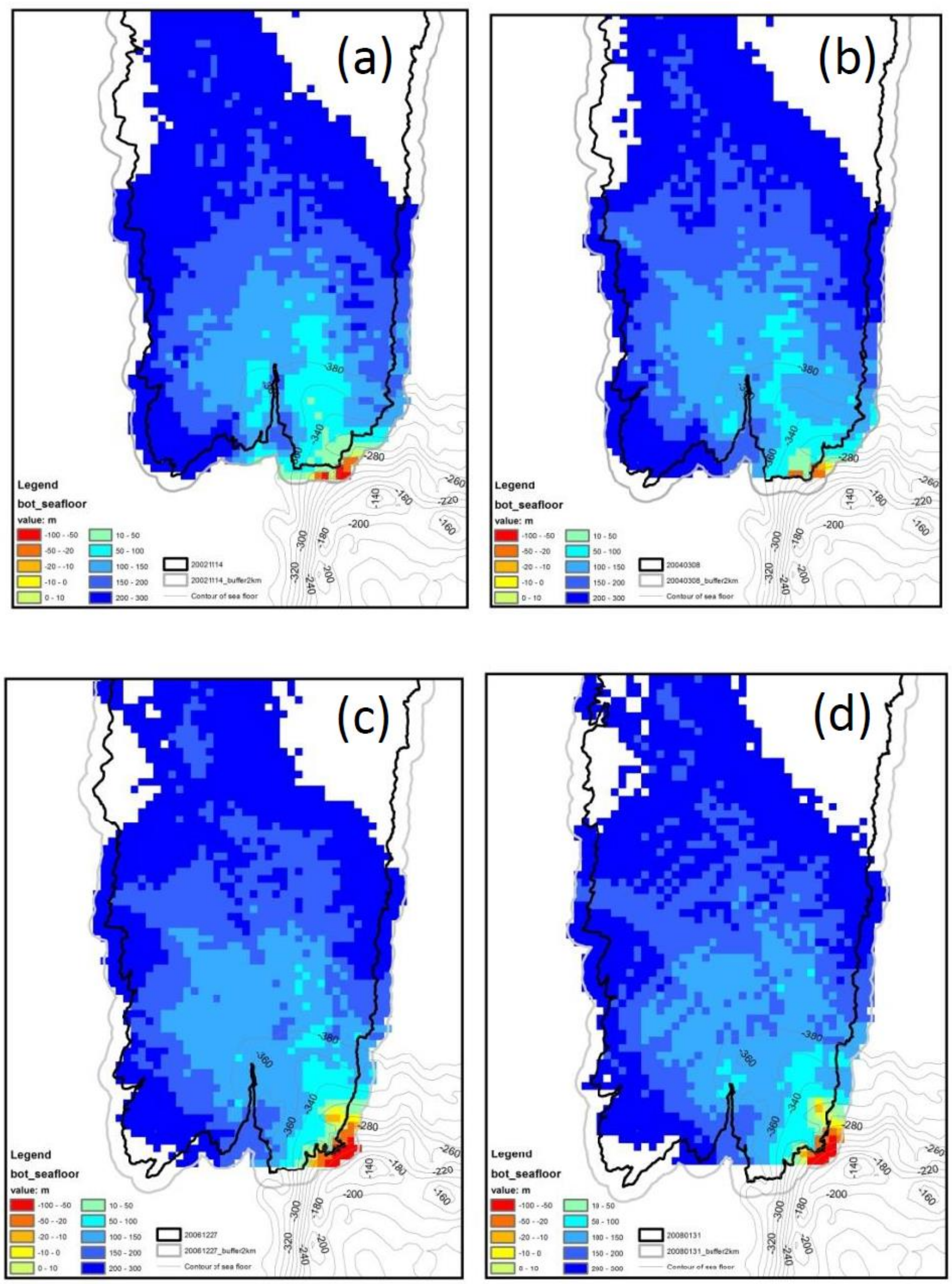
(a)
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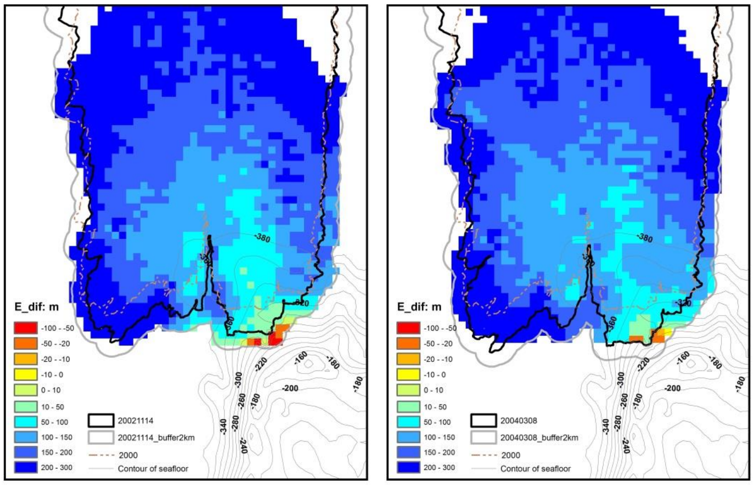
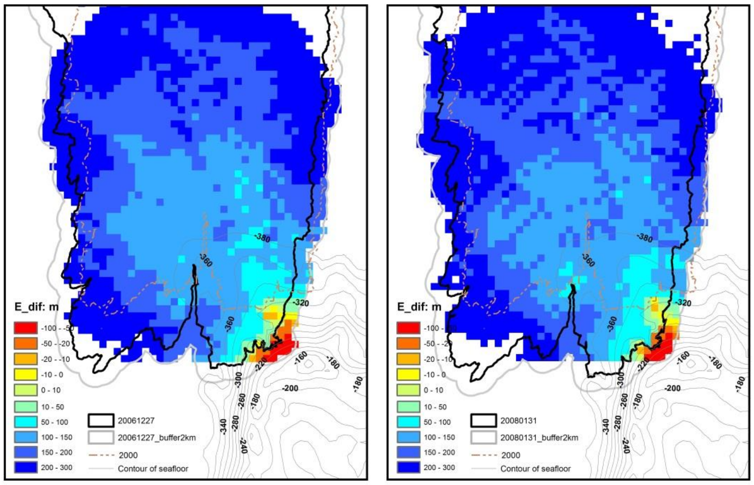
Contour of sea floor



(a) (b)



(c) (d)

Figure ~~5~~6. Elevation difference of Mertz ice bottom and seafloor topography. (a), (b), (c) and (d) correspond to elevation difference assuming hydrostatic equilibrium under the minimum sea

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Formatted: Font: (Default) Times New Roman, 12 pt surface height -3.35 m on November 14, 2002 , March 8, 2004, December 27, 2006, and January 31, 2008, respectively. The contours in the lower right indicate seafloor topography (unit: m) of the Mertz Bank with an interval of 20 m. The solid black line indicates the boundary of the MIT and the thick gray line outlines a buffer region of the boundary with 2 km as buffer radius. The dash-dotted line indicates the shape of the MIT on January 25, 2000, which is used to identify the bathymetry gap under the ice tongue. In the legend, negative values mean that ice bottom is lower than the seafloor, which of course is impossible. Therefore, the initial assumption of a floating ice tongue was incorrect in those locations (yellow to red colors), and the ice was grounded. Regions with more negative values indicate more heavily grounding inside of the MIT or more heavily grounding potential in the buffer region.

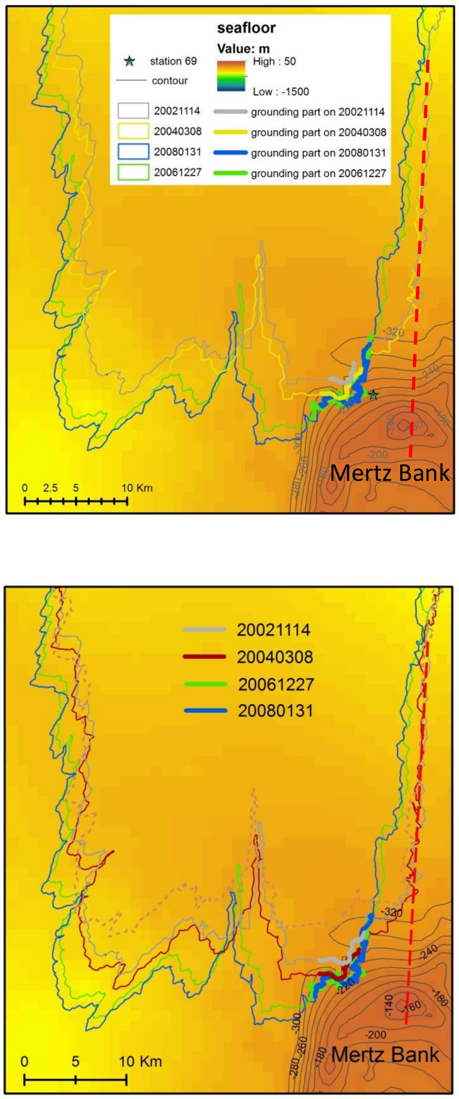


Figure ~~6~~7. Digital Elevation Map (DEM) of seafloor around Mertz and grounding section of the boundaries extracted from 2002 to 2008. The grounding sections of the MIT boundary in 2002, 2004, 2006 and 2008 is marked with thick gray, purple, green and blue polylines respectively and MIT boundaries are indicated with polygons with the same legend as Fig. 3. Additionally, MIT boundary in 2000 indicated with dash-dotted polygon is used to show the different quality of seafloor DEM. Inside of this polygon no bathymetry data was collected or used. The dashed red line indicates the ‘extension line’ of the west flank of MIT on November 14, 2002, passing the shallowest region of the Mertz Bank (about -140 m).

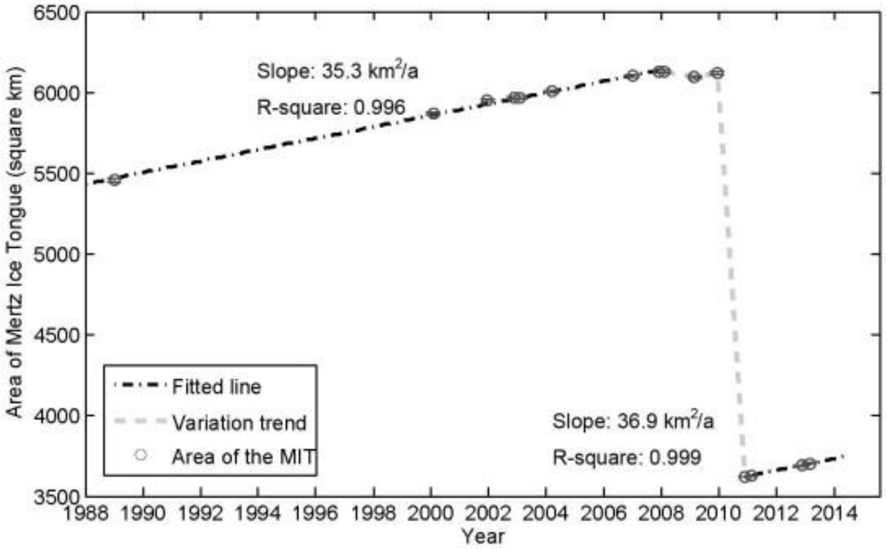
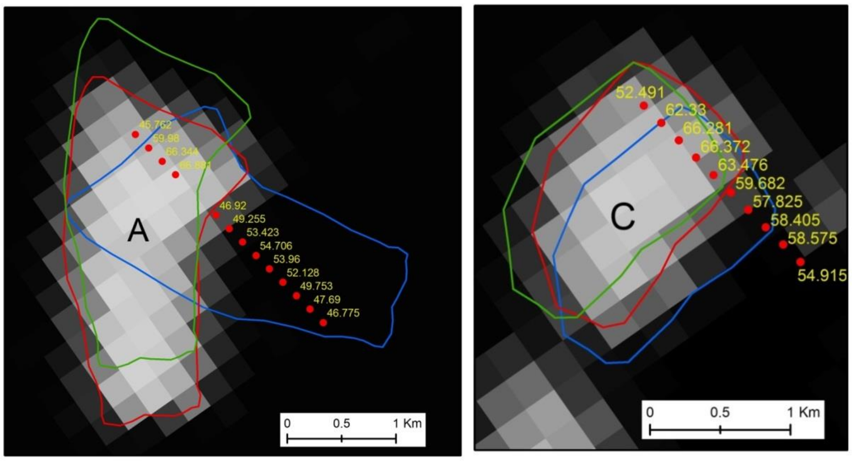
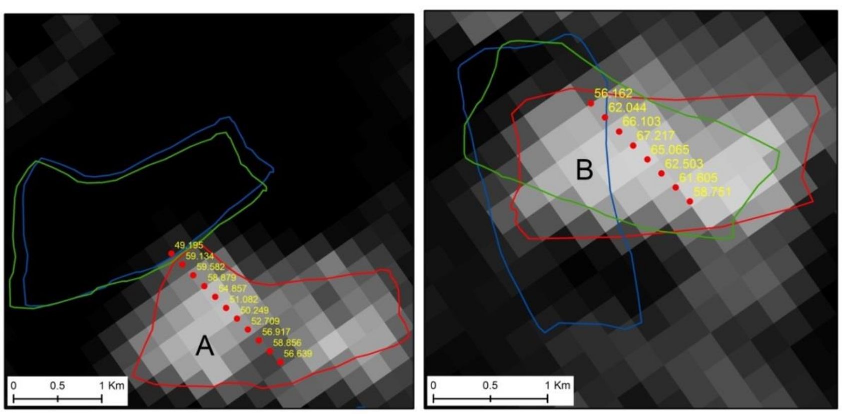


Figure 78. Time series of area change of the MIT. The area covers the entire ice tongue, to the grounding line as indicated with thick blue line in Figure Fig. 3. The area is extracted from Landsat images from 1988 to 2013.



(a) (b)



(c) (d)

Figure 9. Freeboard extraction results from ICESat/GLAS for icebergs ‘A’, ‘B’ and ‘C’ in 2006 and 2008 respectively. (a) and (b) correspond to freeboard measurements from ‘A’ and ‘C’ respectively on February 23, 2006 (2006054), with background image from MODIS captured on 2006054. (c) and (d) correspond to freeboard measurements from ‘A’ and ‘B’ respectively on February 18, 2008 (2008049), with background image from MODIS captured on 2008050. The

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location of each iceberg in different observation time is indicated with different colored polygons, the legend of which is the same as what is used in Fig. 4. Inside of each sub-figure, different icebergs are marked with capital characters ‘A’, ‘B’ and ‘C’ respectively and iceberg freeboard results in unit of meter are marked in yellow.

Tables

Table 1. Statistics of the three icebergs used to inverse FAC with least-square method. Icebergs 'A', 'B' and 'C' are the same as what are used in Fig. 4 and 9. Measurements from icebergs 'A' and 'C' in February 2006 are used to derive FAC with least-squares method. Icebergs 'A' and 'B' in 2008 are used for validation.

Icebergs	date	Latitude (°)	Longitude (°)	Freeboard (m)	Seafloor (m)	Sea level (m)	ε (m)	E_{dif} (m)
A	Feb 23, 2006	-67.1737	146.6595	66.88	-528.48	-1.92	0.89	
		-67.1752	146.6604	66.34	-527.01	-1.92	1.30	
C	Feb 23, 2006	-67.1085	146.6247	66.37	-505.84	-1.92	-1.25	
		-67.1100	146.6255	66.28	-507.08	-1.92	-1.01	
A	Feb 18, 2008	-67.1194	146.6303	58.88	-522.52	-2.08		69.14
		-67.1209	146.6311	59.58	-524.16	-2.08		64.88
B	Feb 18, 2008	-67.0906	146.6151	67.22	-500.92	-2.08		-22.45
		-67.0921	146.6159	66.10	-500.47	-2.08		-13.55

Icebergs	date	Latitude (°)	Longitude (°)	Freeboard (m)	Seafloor (m)	Sea level (m)	E_{dif} (m)
A	Feb 23, 2006	-67.1737	146.6595	66.88	-528.48	-1.92	7.93
		-67.1752	146.6604	66.34	-527.01	-1.92	10.96
C	Feb 23, 2006	-67.1085	146.6247	66.37	-505.84	-1.92	-10.44
		-67.1100	146.6255	66.28	-507.08	-1.92	-8.44
A	Feb 18, 2008	-67.1194	146.6303	58.88	-522.52	-2.08	69.14
		-67.1209	146.6311	59.58	-524.16	-2.08	64.88

B	Feb 18, 2008	-67.0906	146.6151	67.22	-500.92	-2.08	-22.45
		-67.0921	146.6159	66.10	-500.47	-2.08	-13.55

Table 2. Statistics of grounding grids inside or grounding potentials outside of the Mertz Ice Tongue (MIT) ('I': inside of thick black line, Fig. ~~5~~6; Number in brackets indicates how many grids are located inside of the 2000 Mertz boundary; 'O': between the black and gray lines, Fig. ~~5~~6) on November 14, 2002, March 8, 2004, December 27, 2006 and January 31, 2008 respectively. Each grid covers an area of 1 km^2. The Mean, Minimum and Standard deviation is calculated without considering those fallen inside of the 2000 Mertz boundary, but only those having elevation difference less than 46 m and out of 2000 Mertz boundary.

~~Elevation difference (subtracting seafloor from ice bottom)~~	~~2002-11-14~~		~~2004-03-08~~		~~2006-12-27~~		~~2008-01-31~~	
	~~I~~	~~O~~	~~I~~	~~O~~	~~I~~	~~O~~	~~I~~	~~O~~
~~17-34(m)~~	~~4~~	~~5~~	~~4~~	~~2~~	~~7~~	~~1~~	~~3~~	~~5~~
~~0-17 (m)~~	~~2~~	~~6~~	~~1~~	~~1~~	~~6~~	~~2~~	~~4~~	~~2~~
~~<0 (m)~~	~~0~~	~~8~~	~~2~~	~~5~~	~~7~~	~~21~~	~~6~~	~~18~~
~~Mean (m)~~	~~25.0~~	~~-11.9~~	~~8.9~~	~~-6.4~~	~~3.8~~	~~-42.1~~	~~-0.8~~	~~-31.0~~
~~Minimum (m)~~	~~11.9~~	~~-81.5~~	~~-46.0~~	~~-44.5~~	~~-52.3~~	~~-102.8~~	~~-34.8~~	~~-103.0~~
~~Standard deviation (m)~~	~~8.4~~	~~37.8~~	~~28.0~~	~~27.1~~	~~21.8~~	~~36.4~~	~~19.9~~	~~38.0~~
~~Number of grids~~	~~6~~	~~19~~	~~7~~	~~8~~	~~20~~	~~22~~	~~13~~	~~25~~

Elevation difference (subtracting seafloor from ice bottom)	2002-11-14		2004-03-08		2006-12-27		2008-01-31	
	I	O	I	O	I	O	I	O
23-46 (m)	9(3)	10(0)	6(0)	3(0)	10(1)	1(0)	10(3)	5(0)
0-23 (m)	2(0)	6(0)	1(0)	1(0)	9(0)	2(0)	4(0)	2(0)
<0 (m)	0(0)	8(0)	2(0)	5(0)	7(0)	21(0)	6(0)	18(0)
Mean (m)	28.8	9.8	15.8	-1.1	10.9	-41.9	12.3	-31.0
Minimum (m)	11.9	-81.5	-46.0	-44.5	-52.3	-102.8	-34.8	-103.0

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Standard deviation (m)	9.2	36.8	29.6	31.4	24.7	37.6	27.3	38.0
Number of grids	8	24	9	9	25	24	17	25

Table 3. Statistics of grounding outlines of the MIT as shown with thick polylines in Fig. ~~6~~ 7 on November 14, 2002, March 8, 2004, December 27, 2006 and January 31, 2008 respectively

	2002-11-14	2004-03-08	2006-12-27	2008-01-31
Start location (°)	146.~~160~~124 °E, 66.~~689~~696 °S	146.155 °E, 66.681 °S	146.093 °E, 66.700 °S	146.~~108~~088 °E, 66.~~695~~699 °S
End location (°)	146.~~222~~240 °E, 66.~~689~~693 °S	146.256 °E, 66.683 °S	146.304 °E, 66.669 °S	146.~~271~~292 °E, 66.~~675~~668 °S
Perimeter (km)	~~4.2~~7.0	6.4	24.7	~~18.0~~20.9