Supporting Information for

Four-decade record of pervasive grounding line retreat along the Bellingshausen margin of West Antarctica

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Contents of this file

Figures S1 to S4
Text S1 to S3
Tables S1 to S3
Dataset S1

Additional Supporting Information (Files uploaded separately)

Dataset S1
Tables S1 and S4

Introduction

This file contains additional information pertaining to the derivation, analysis and interpretation of the results presented in this study. Landsat, ERS-1/2 Synthetic Aperture Radar (SAR), Operation IceBridge and CryoSat-2 data were acquired between 2013 and 2016 from publically available NASA and ESA data repositories. MODIS MOA and Bedmap2 data products were obtained from the NSIDC data portal and the SCAR Antarctic Digital Database, respectively. Detection of grounding line (GL) change was completed using standard GIS software and SAR processing was carried out using commercial Interferometric Synthetic Aperture Radar (InSAR) processing tools. At time of publication, the authors declare no known imperfections or anomalies within the data sets.
Figure S1. Visual summary of break-in-slope mapping. 

a, Landsat scene acquired on 20 February 1991. Image shows a clearly identifiable break-in-slope between the grounded ice (eastern Thurston Island) and adjacent, floating ice. Two grounded ice rises are also visible. 

b, The break-in-slope is digitized for year c.1990, and represents Point I_b. 

c, This process was carried out along the whole BSS and was repeated for all other epochs, using Landsat imagery acquired during 1975 (not available in this location hence not depicted in the example above), c.1985, 2000, 2005, 2010 and 2015.
Figure S2. Double differential interferogram showing Abbot Ice Shelf and eastern Sherman Island, processed using SAR imagery acquired on 19920123-19920126 and 19920129-19920201 (3-day temporal baseline). The absolute limit of tidal flexure (\( F \); blue line) is delineated by the landward limit of closely-spaced fringes observed between the freely-floating ice shelf and fully-grounded ice [cf. Fricker et al., 2009; their Figure 2].
Figure S3. Examples of $I_b$ migration and comparison with InSAR-derived $F$ at selected locations in the BSS. Boxes in top panel are color-coded to correspond with matching color-bordered inset panels. Labelled sites as per Figure 1. 1975/1985 $I_b$ lines are absent in some panels due to the lack of Landsat spatial coverage during these epochs. Top panel is superimposed on the MOA2004 continental outline [Haran et al., 2013], and black lines delineate the 2008/2009 MOA GL [Haran et al., 2014]. All other panels are superimposed over MOA2004 [Haran et al., 2013]. Inset (bottom right): study location.
Figure S4. Rates of thickness change (δT/δt) over selected profiles in Eltanin Bay, derived from CryoSat-2 observations and Landsat-derived GL thinning estimations for the period 2010-2015 (refer to Text S3 for more information on estimating Landsat and CryoSat-2 thinning rates). Inset shows Eltanin Bay and locations of profiles shown in graph. Fox, Ferrigno and Alison Ice Stream drainage catchments shown in gray. Colored GLs and corresponding numbers refer to selected 30 km segment sites within the Eltanin Bay region, as discussed in main text and Data Set S1.
**Text S1. Quantification of Landsat positional accuracy**

Following *Bindschadler* et al. [2011], error in the mapping of Point \( I_b \) is dependent on the nature of the grounded-ice boundary and the geometric error associated with each Landsat satellite platform (i.e. the orbital/geo-positional error associated with successive Landsat passes; cf. *USGS* [2015]), assuming tidal variation in the position of the grounding zone to be negligible. Hence, where the boundary transition is from grounded ice to open ocean, we mapped \( I_b \) to within one Landsat scene pixel (i.e. a prescribed one pixel error; where pixel value is dictated by the spatial resolution of the satellite sensor used (Table S2)). For grounded-ice/sea-ice transitions, where the boundary is potentially more ambiguous, we mapped to within two Landsat pixels of error. At the deeply bedded Ferrigno Ice Stream, where ice velocities exceed 1 km yr\(^{-1}\) [*Rignot* et al., 2008; *Williams* et al., 2014] and the break in slope is more ambiguously located compared to neighboring (more steeply bedded) locations, we assigned a 500 m error boundary in accordance with *Bindschadler* et al. [2011]. Along the remaining boundaries of the BSS coastline, we prescribed a three-pixel error. These include regions of slow-flowing grounded ice flowing into ice shelves and some outlet glaciers where \( I_b \) is more readily identifiable than faster flowing ice streams.

Accordingly, following the discussion in *Bindschadler* et al. [2011], estimations of positional error (1σ) were calculated as the root-sum-square of \( I_b \) delineation accuracy and satellite geometric error. These create the positional accuracy estimations found in Table S2.

In order to propagate error between successive \( I_b \) observations (e.g. the results shown in Figure 1), we calculated the root-sum-square of the (1σ) positional errors associated with Landsat 8 (i.e. for the 2015 baseline, refer to main text Section 2.3) and the earlier Landsat platform under analysis for a given epoch. Thus, for example, in Figure 1, the majority of accumulative errors in the BSS equal 137 m, as the grounding line boundary type is classed as ‘Slow-ice-to Shelf or Outlet Glacier’ (Table S2; e.g. \( \sqrt{91^2 + 103^2} \)). For Figure 2, scaled error approximations were derived by dividing these errors by the temporal period under question.
**Text S2.** \( I_b \) change quantification: Calculation of 5- to 10-year change.

Following completion of the \( I_b \) change calculations detailed in the main text (section 2.3), changes in \( I_b \) position over 5- to 10-year periods were calculated using the following expression:

\[
\frac{\delta I_b}{\delta t} = \frac{\delta I_b[2015-y_0] - \delta I_b[2015-y+1]}{\delta t}
\]  

[1]

where \( \delta I_b/\delta t \) corresponds to the change in \( I_b \) per 30-km segment over 5- to 10-year period; \( \delta I_b[2015-y_0] \) is the change in \( I_b \) over the earliest epoch under examination (e.g. change in 2005 GL to the baseline 2015 GL); \( \delta I_b[2015-y+1] \) is the change in \( I_b \) over the immediately succeeding epoch (e.g. 2010 to 2015); and \( \delta t \) is the temporal period between the two epochs. Refer to Data Set S1 and Figure 2 for raw data and examples of this process.

Notably, owing to the limited spatial and/or temporal availability of Landsat imagery across some regions of the BSS (especially for 1975), the above processes were not carried out in sectors containing no [2015-\( y \)] data for one or both epochs under analysis.
Text S3. CryoSat-2-derived elevation change for ice draining into Eltanin Bay, and comparisons with 2010-2015 Landsat-derived estimations of ice thinning at the GL.

Rates of surface elevation change were generated from swath processing of CryoSat-2 data acquired between 2010 and 2015. Swath processing is enabled by the Synthetic Aperture Radar Interferometric (SARIn) mode of CryoSat-2 and enables one to two orders of magnitude more elevation measurements than conventional point-of-closest-approach (hereafter POCA) altimetry techniques, thereby allowing increased spatial and temporal resolution and improved coverage of ice-sheet marginal areas [Hawley et al. 2009; Gray et al. 2013]. Linear rates of surface elevation change were then derived at 500 m posting using a repeat track approach [McMillan et al., 2014]. Across Eltanin Bay, where we detect the greatest changes in GL position over the observational period 2010-2015, we extracted 3 profiles across the Ferrigno and Fox catchment regions (Figure S4). These profiles reveal increasing trends of rates of surface elevation change (\(\delta T/\delta t\)) towards the GL, with maximum values occurring at Ferrigno West (\(-6.40 \text{ m yr}^{-1}, \sigma = \pm 0.49 \text{ m yr}^{-1}\); Figure S4). Notably, average \(\delta T/\delta t\) across all 3 profiles equals \(-0.84 \text{ m yr}^{-1}\) (\(\sigma = \pm 0.21 \text{ m yr}^{-1}\)), which compares well with previously reported CryoSat-2 POCA observations in this area [McMillan et al., 2014; Wouters et al., 2015].

In addition to CryoSat-2-derived \(\delta T/\delta t\), theoretical thinning rates over the same epoch (2010-2015) were calculated using our Landsat-derived observations of \(I_b\) change. Rates were calculated using the empirical formula detailed in Park et al. [2013], whereby theoretical \(\delta T/\delta t\) is a function of GL retreat, surface topography/slope, subglacial bed topography/slope, seawater density (1027.5 kg m\(^{-3}\)) and the density of ice (917 kg m\(^{-3}\)). Our calculations utilized surface and bed slopes inferred from BEDMAP2 [Fretwell et al., 2013], and produced the theoretical estimations shown in Figure S4.

Overall, our estimations show excellent agreement with CryoSat-2 swath observations at Ferrigno East and Fox, indicating increasing trends of negative \(\delta T/\delta t\) towards the GL at these locations. The high Landsat-derived \(\delta T/\delta t\) value calculated for Ferrigno West (\(-9.8 \text{ m yr}^{-1}\)) is believed to be subject to error, associated with the dramatic break up of ice and corresponding GL retreat across this sector between 2010 and 2015 (Figure 2; Figure S3). Nonetheless, the close agreement between Landsat and CryoSat-2 thinning values at Ferrigno East and Fox supplements other independent observations of dynamic thinning across the Eltanin Bay region in recent years [Rignot et al., 2008; Bingham et al., 2012; McMillan et al., 2014, Wouters et al., 2015], and acts as auxiliary validation of our Landsat \(I_b\) mapping.
Table S1. Landsat data used in the present study.

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| Platform       | Year Mapped | Grounded Ice Boundary Classification                      | Spatial Resolution (m) | Prescribed Pixel Error (m) | Geometric Error¹ (m) | Positional Error (1σ; m) |
|---------------|-------------|----------------------------------------------------------|------------------------|----------------------------|----------------------|-------------------------|
| Landsat 2 (MSS³) | 1975        | Open ocean                                               | 1 (60)                 | 117                        |                      |                         |
|               |             | Grounded-ice/Sea-ice                                     | 2 (120)                | 156                        |                      |                         |
|               |             | Slow-ice-to Shelf or Outlet Glacier                      | 60                     | <100                       | 206                  |                         |
|               |             | Fast flowing, deeply bedded grounded ice                 | 500                    | 510                        |                      |                         |
| Landsat 4,5 (TM³), 7 (ETM+⁴) | 1985, 1990, 2000, 2005, 2010 | Open ocean                                               | 1 (30)                 | 58                         |                      |                         |
|               |             | Grounded-ice/Sea-ice                                     | 2 (60)                 | 78                         |                      |                         |
|               |             | Slow-ice-to Shelf or Outlet Glacier                      | 30                     | <50                        | 103                  |                         |
|               |             | Fast flowing, deeply bedded grounded ice                 | 500                    | 502                        |                      |                         |
| Landsat 8 (OLI⁵) | 2015        | Open ocean                                               | 1 (30)                 | 32                         |                      |                         |
|               |             | Grounded-ice/Sea-ice                                     | 2 (60)                 | 61                         |                      |                         |
|               |             | Slow-ice-to Shelf or Outlet Glacier                      | 30                     | 12                         | 91                   |                         |
|               |             | Fast flowing, deeply bedded grounded ice                 | 500                    | 500                        |                      |                         |

¹Geometric error values derived from Lee et al. [2004]; Tucker et al. [2004], Bindschadler et al. [2011], Storey et al. [2014]. ²Multispectral Scanner. ³Thematic Mapper. ⁴Enhanced Thematic Mapper Plus. ⁵Operational Land Imager

Table S2. Landsat platform-specific positional accuracy (1σ) estimations for BSS grounded ice boundary classifications.
Table S3. ERS-1/2 Synthetic Aperture Radar imagery used to make double-differential interferograms.

(File uploaded separately as 2016GL068972-ts03.pdf)
Data Set S1. GL change values generated in this study.

File uploaded separately as 2016GL068972-ds01.xlsx
References

Bindschadler, R., et al. (2011), Getting around Antarctica: New high-resolution mappings of the grounded and freely-floating boundaries of the Antarctic Ice Sheet created for the International Polar Year, Cryosphere, 5, 569-588, http://dx.doi.org/10.5194/tcd-5-183-2011.

Bingham, R.G., F. Ferraccioli, E.C. King, R.D. Larter, H.D. Pritchard, A.M. Smith, and D.G., and Vaughan (2012), Inland thinning of West Antarctic Ice Sheet steered along subglacial rifts, Nature, 487, 468-471, doi:10.1038/nature11292.

Ferrigno, J.G., A.J. Cook, A.M. Mathie, R.S. Williams, Jr., C. Swithinbank, K.M. Foley, A.J. Fox, J.W. Thomson, and J. Sievers (2009), Coastal-Change and Glaciological Map of the Palmer Land Area, Antarctica: 1947–2009 and accompanying explanatory pamphlet, US Geological Survey, USA, Geologic Investigations Series Map I–2600–C.

Fretwell, P., et al. (2013), Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica, Cryosphere, 7, 375–393, doi:10.5194/tc-7-375-2013.

Fricker, H.A., et al. (2009), Mapping the grounding zone of the Amery Ice Shelf, East Antarctica using DInSAR, MODIS and ICESat, Antarct. Sci., 21(5), 515–532, doi: 10.1017/S095410200999023X.

Gray, L., D. Burgess, L. Copland, R. Cullen, N. Galin, R. Hawley, and V. Helm (2013), Interferometric swath processing of CryoSat-2 data for glacial ice topography, The Cryosphere Discussions, 7, 3133-31621857-1867.

Haran, T., J. Bohlander, T. Scambos, T. Painter, and M. Fahnestock (2005, updated 2013), MODIS Mosaic of Antarctica 2003-2004 (MOA2004) Image Map, digital media, Boulder, Colorado, USA: National Snow and Ice Data Center. http://dx.doi.org/10.7265/N5ZK5DM5.

Haran, T., J. Bohlander, T. Scambos, T. Painter, and M. Fahnestock (2014), MODIS Mosaic of Antarctica 2008-2009 (MOA2009) Image Map, digital media, Boulder, Colorado, USA: National Snow and Ice Data Center. http://dx.doi.org/10.7265/N5KP8037.

Hawley, R. L., A. Shepherd, R. Cullen, V. Helm, and D. J. Wingham (2009), Ice-sheet elevations from across-track processing of airborne interferometric radar altimetry, Geophys. Res. Lett., 36, L22501.

Lee, D.S., J.C. Storey, M.J. Choate, and R.W. Hayes (2004), Four Years of Landsat-7 On-Orbit Geometric Calibration and Performance, IEEE Trans. Geosci. Remote Sens., 42(12), 2786-2795, doi:10.1109/TGRS.2004.836769.
Leuschen, C., P. Gogineni, F. Rodriguez-Morales, J. Paden, and C. Allen (2010a, updated 2015a), IceBridge MCoRDS L2 Ice Thickness, Version 1, digital media [subset IRMCR_20091103_02], Boulder, Colorado, USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. http://dx.doi.org/10.5067/GDQ0CUCVTE2Q.

Leuschen, C., P. Gogineni, F. Rodriguez-Morales, J. Paden, and C. Allen (2010b, updated 2015b), IceBridge MCoRDS L2 Ice Thickness, Version 1, digital media [subset IRMCR2_20111116_02], Boulder, Colorado, USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. http://dx.doi.org/10.5067/GDQ0CUCVTE2Q.

McMillan, M., A. Shepherd, A. Sundal, K. Briggs, A. Muir, A. Ridout, A. Hogg, and D. Wingham (2014), Increased ice losses from Antarctica detected by CryoSat-2, Geophys. Res. Lett., 41(11), 3988-3905, doi:10.1002/2014GL060111.

Paolo, F.S., H.A. Fricker, and L. Padman (2015), Volume loss from Antarctic ice shelves is accelerating, Science, 348, 327-331, doi:10.1126/science.aaa0940.

Rignot, E., J. L. Bamber, M. R. van den Broeke, C. Davis, Y. Li, W. J. van de Berg, and E. van Meijgaard (2008), Recent Antarctic ice mass loss from radar interferometry and regional climate modelling, Nat. Geosci., 1, 106–110, doi:10.1038/ngeo102.

Rignot, E., J. Mouginot, and B. Scheuchl (2011), Antarctic grounding line mapping from differential satellite radar interferometry, Geophys. Res. Lett., 38, L10504, doi:10.1029/2011GL047109.

Storey, J., M. Choate, and K. Lee (2014), Landsat 8 Operational Land Imager On-Orbit Geometric Calibration and Performance, Remote Sens., 6(11), 11127-11152, doi: 10.3390/rs6111127.

Swithinbank, C., R.S. Williams, Jr., J.G. Ferrigno, K.M. Foley, C.E. Rosanova, and L.M. Dailide (2004), Coastal-change and glaciological map of the Eights coast area, Antarctica: 1972–2001 and accompanying explanatory pamphlet, US Geological Survey, USA, Geologic Investigations Series Map I–2600–E.

Tucker, C.J., D.M. Grant, and J.D. Dykstra, (2004), NASA’s Global Orthorectified Landsat Data Set Compton, Photogramm. Eng. Remote Sens., 70(3), 313-322, doi: 10.14358/PERS.70.3.313.

Wouters, B., A. Martin-Español, V. Helm, T. Flament, J. M. van Wessem, S. R. M. Ligtenberg, M. R. van den Broeke, and J. L. Bamber (2015), Dynamic thinning of glaciers on the Southern Antarctic Peninsula, Science, 348, 899-903, doi:10.1126/science.aaa5727.