Response to the Interactive comment on

"Recent dynamic changes on Fleming Glacier after the disintegration of Wordie Ice Shelf, Antarctic Peninsula"

by Peter Friedl et al.

Anonymous Referee #2
Received and published: 25 October 2017

We would like to thank the reviewer for constructive and helpful comments on our manuscript. All comments have been considered and a list of responses and changes in the manuscript is given below. Responses are written in bold face type and changes in the manuscript are written in *blue*.

Friedl et al. present a dense time series of surface velocities and elevation change rates of the Fleming Glacier system in the past two decades from multi-source remote sensing data. This study identified two significant acceleration phases occurred in 2008 and 2010-2011 after the Wordie Ice Shelf has nearly disappeared in front of the Fleming Glacier. The determination of floating area based on the hydrostatic height anomalies, bedrock data, elevation change rates, and acceleration phase is very helpful to explain the rapid dynamic changes after 2008. However, some points in this study are not well explained and need further rewording. Some minor wording and grammar errors also need to be fixed.

General Comments:

1) It is not clear about the epoch of the 2008 grounding line position. Please clarify it, particularly regarding locations in Fig. 6 and Fig. 6S.
We have added more information on how we decided the groundling line locations in 2008 to the methods section (Sect. 4.3) and especially to the discussions on Fig. 6S. We are aware that the exact 2008 grounding line positions are vague and we have tried to make this clearer in the text. However, since the glacier front had retreated behind the grounding line 1996 in 2008 for the first time, the 2008 grounding line must have been situated upstream of the 1996 position.

2) The method used to determine the grounding line position in 2008, 2011 and 2015 from the velocity data, surface-thinning rate, and the bedrock data is not clear enough in the method (Sect. 4.3, P7, L19-27) and result section (Sect. 5.3), especially regarding the determination of the grounding line position in 2008. From Fig. 6, it is appeared that the 2015 grounding line is mainly based on the ridges of modelled bedrock combined with the hydrostatic height anomalies along OIB flight lines. However, profiles in Fig. S5 show that how much the Bedmap2 bedrock and Huss and Farinotti's modelled bedrock can differ from the PIB and OIB measurements. Then how reliable are the hills used to decide the grounding line location? In the analysis of Fig. 6S, it is better to explain how the different evidence (velocity profiles, elevation change profiles, hydraulic height anomalies, and modelled bedrock) is being combined to determine the estimated 2008 and 2015 grounding line. If they are not consistent with each other, please explain the final selection.
We have largely rewritten Sect. 4.3 Sect. 5.3 and the discussions to Fig. S6 a-d in order to better explain how we finally decided the grounding line positions. We have also addressed possible uncertainties in the bedrock data.

3) This study (P11, L27-29) concludes that the basal melting driven by ocean-warming is the dominant trigger of the grounding line retreat and glacier acceleration. However this lacks direct evidence, namely the basal or frontal melting rates underneath the ice shelf. Given the little ice shelf left in 2008, it is not very convincing to say that the basal melting underneath the ice shelf dominates the ungrounding process.

We understand the reviewer`s concerns. However, Depoorter et al. (2013) and Rignot et al. (2013) calculated high basal melt rates of 14.79 ± 5.26 m/a and 23.6 ± 10 m/a respectively for the remaining parts of the ice shelf. These melt rates are similar to those found for ice shelves in the Amundsen Sea sector (Table 1 in Suppl. Material and Fig. 2, Depoorter et al., 2013).). Hence, it is likely that basal melt also occurs at the grounding line. Furthermore the coincident timing of exceptional warm water intrusions in 2008/2009 and 2010/2011 into Marguerite Bay found by Walker and Gardner (2017) and the two acceleration phases found by us, indicates that ocean warming and the observed changes in glacier dynamics are strongly correlated. Anomalously low sea ice extent in Marguerite Bay, observed in 2008 and 2010, indicates that the warming events affected the upper water column, but Walker and Gardner (2017) found that the years 2009-2011 had the highest temperatures also at depths of > 400 m. Hence, it is very likely that submarine ice melting at the grounding line was increased during phases of strong CDW upwelling events and that this has triggered unpinning in 2008 and gradual grounding line retreat between 2010 and 2011. We rewrote the Discussion, Conclusion and Abstract sections in such a way that it points out that our conclusion on basal melt at the grounding line is not based on direct observations made in this study but on reasonable assumptions upon existing evidence.

Specific Comments:

P1, L8: change to ". . . regions most affected by climate change"
The sentence has been changed accordingly.

P1, L14: The finding about glacier ungrounded in 2008 between January and March has not been confirmed by observation or measurements. Please reedit this sentence.
The glacier front had retreated behind the 1996 grounding line location for the first time in 2008. Hence, the grounding line must have been located upstream of its 1996 position by this time. Before 2008 no marked changes in surface velocity have been observed, which would have indicated grounding line retreat. Although the precise position of the grounding line after the acceleration in 2008 remains vague, at least it is clear that in 2008 the grounding line was located upstream of its 1996 position. It is likely that confirmed intrusions of warm CDW to Maguerite Bay in 2008 have triggered unpinning of the glacier tongue from a pinning point located at the 1996 grounding line position. However, the sentence has been reformulated during rewriting of the abstract.

P1, L24: "Currently, the tongue of Fleming Glacier is grounded in a zone of bedrock elevation of -400 m" This statement is not mentioned in the main text. Please state this in the main text and make the elevation color bar in Fig. 6 clearer for reading the elevation values. It will be helpful to add elevation contours.
We thank the reviewer for this helpful suggestion. We have added elevation contours and a more detailed color bar to Fig. 6. We have also added a note on the elevation level of the recent grounding line (~-400 to -500 m) to the main text (section 5.3):
For most regions of the glacier tongue we estimate the current grounding line to coincide with these ridges at an elevation between ~-400 and -500 m.

P1, L26: You can't say "this endangers" "a huge potential". Add a suitable verb before "a huge potential". "huge" is not appropriate here.
We have changed the sentence into:
Hence, this endangers upstream ice masses, which can significantly increase the contribution of Fleming Glacier to sea level rise in the future.

P2, L4: Add "be" before the number "4.21".
We have changed the sentence accordingly:

P3, L3: “former tributary glaciers” is confusing since the glaciers still exist, Suggest instead “. . . originally fed by several major tributary glaciers (Fig.1). Among these, Fleming Glacier is . . .”.
We have changed this accordingly.

P3, L10: “Here the ice shelf was temporarily grounded and stabilized . . .” is confusing. Does “Here” mean at a time point or at the location of the pinning points? Is there evidence of grounding of the previously floating Wordie Ice Shelf? Do you mean it was stabilized temporarily? Do you mean “the next rapid break up event” occurred in 1989? If yes, please specify it.
We apologize for the ambiguous phrasing. “Here” refers to the location of the pinning points (e.g. ice rises/rumples). Based on the analysis of satellite imagery e.g. Vaughan (1993) concluded that the ice front retreat of Wordie Ice Shelf was punctuated by periods of stasis during which the ice front rested on theses pinning points. When embedded in the ice shelf they helped to stabilize the ice shelf by compressing it upstream and providing restraint at the grounding line. However, during the following rapid break up events (not just the 1989 event) the ice rises appeared to behave as indenting wedges, contributing to weakening the ice shelf and accelerating break up. We have reformulated the section into:
Analyses of satellite imagery suggest that the ice shelf was temporarily grounded and stabilized at these pining points until one of the next rapid break-up events took place (Doake and Vaughan, 1991; Reynolds, 1988; Vaughan, 1993; Vaughan and Doake, 1996). However, during phases of ice front retreat, instead of protecting the ice shelf against decay, ice rises that were embedded in the ice shelf appeared to behave as indenting wedges, contributing to weakening the ice shelf and accelerating break up (Doake and Vaughan, 1991; Vaughan, 1993).

P3, L18-19: Please add the ice front position in 1997 and 2000 in Fig. 1. It will help reader to understand your statement here.
We have changed Fig. 1 accordingly.

P4, L21-25: The information about the modelled bedrock topography from Huss and Farinotti 2014 is not enough. Given its role, indication of origins and uncertainties should be included in the paper.
We agree with the reviewer. We have added more detailed information on the dataset to the corresponding section:
The dataset was generated by subtracting modelled ice thickness from the improved ASTER GDEM by Cook et al. (2012). Ice thickness was derived by constraining a simple model based on the shallow ice approximation for ice dynamics with observational data of ice thickness (OIB) and surface velocity (Rignot et al., 2011). Where available the modelled ice thickness was corrected with OIB ice thickness data, leading to more precise ice thickness values in such areas. On average, the local uncertainty in ice thickness of the dataset is ±95m but values can reach ±500m for deep troughs without nearby OIB measurements. Since OIB coverage is fairly good across Fleming Glacier, uncertainties in modelled ice thickness are relatively low in this area. However, a comparison of bedrock elevations from Huss and Farinotti with bottom elevations calculated from OIB ATM and CoRDS measurements shows that although the modelled bedrock reflects the general subglacial topography well, the absolute difference in bottom elevation can be even more than 100 m (Fig. S5). One possible reason for this is a difference between ATM heights and the refined ASTER GDEM, which transfers to bedrock elevation.

P7, L18: Modify “Sect. S2” to “Sect. S3”.
We have changed this.

P7, L22: “mitigates” is hardly correct for 90
We have substituted “mitigates” by “decreases”.

P7, L22-23: It is not clear how you decide the grounding line position from the surface velocities. Please clarify. If you define the grounding line based on where the maximum velocity increase occurred, please specify it with relevant references.

We have added some more sentences with references on how and why information on surface velocity can be used to identify the grounding line:

Moreover, the grounding line marks the transition between two fundamentally different flow regimes of grounded and freely floating ice. Whereas the flow dynamics of grounded ice are dominated by vertical shear and controlled by basal drag, flow of floating ice is drag free and dominated by longitudinal stretching and lateral shear (Schoof, 2007). The difference in flow dynamics of grounded and floating ice can result in pronounced changes in surface velocity close to the grounding line (Stearns, 2007; Stearns, 2011). Moreover, Rignot et al. (2002) demonstrated that if ungrounding occurs, the resulting flow acceleration usually affects both the floating and the grounded part of the glacier, but is largest near the grounding zone. Thus, velocity profiles can serve as additional information for locating the grounding line (Stearns, 2007; Stearns, 2011).

P7, L23: replace “determent” - do you mean “determinant”?

The word has been deleted during rewriting of the section.

P8, L18: Please comment on the higher velocity changes in the 2011 glacier front in Fig. 3 and why it is ignored.

We thank the reviewer for this helpful question. In 2011 the glacier front had an all-time minimum position. Consequently in 2007 and 2015 the ice front was located seaward of the 2011 front. Ice velocities are highest at the glacier front. Hence, at the location of the 2011 front inherently high front velocities were subtracted from inherently lower velocities of floating ice (2011-2015) or vice versa (2007-2011). This results in peaks of velocity change at the 2011 front position. Thus the strong velocity changes at the 2011 front do not represent “real” dynamic change and were ignored. We have added a note on this in the text. Furthermore, we have modified Fig. 3 a, b in such a way that we now do not show velocity change for 2007-2011 and 2011-2015 seaward of the 2011 front anymore. Otherwise here velocity change would result from comparing velocity of the glacier tongue with velocities of sea ice or ice melange.

Fig. 3a, b show absolute and relative velocity changes along the centreline profile for the periods 1995–2007, 2007–2011 and 2011–2015. In 2011 the location of the glacier front reached its most inland position. Consequently velocities measured on sea ice or ice mélange in 2011 (seaward of the 2011 front) were excluded from our analyses. Large changes in surface velocity close to the 2011 front in the periods 2007–2011 and 2011–2015 do not represent real dynamic change, but result from comparing the inherently higher frontal velocities in 2011 with lower velocities of the floating glacier tongue in 2007 and 2015.

P8, L23-24: Suggest updating Table2 by adding the velocity in 2015 from Walker and Gardner, 2017 at three sites.

We have updated the table and have added a note on the higher velocities in 2015 at the three sites to the text:

However, surface velocities derived from Landsat 8 feature tracking suggest that in 2015 velocities at the three measuring sites had increased by ~20% in comparison to 2008 (Walker and Gardner, 2017; Zhao et al., 2017) (Tab. 2).

P8, L27: As I could tell, the highest ice thinning rates for Fleming Glacier from Fig. 4 (orange color) is higher than 6 m a^{-1}.

The reviewer is right. We apologize for the imprecise formulation. We have changed the sentence into:

On Fleming Glacier the highest ice thinning rates with peak values of more than ~6 m a^{-1} were recorded in a zone extending from ~8 to ~14 km upstream.

P9, L2: “For the location of the data see Fig. 4” ! “The location of the data is shown in Fig. 4”.

We have changed this.

P9, L13: Missing space after the full stop.
We have added a space.

P9, L19-20: It would be useful to compare your thinning rate with that from Zhao et al., 2017 and Walker and Gardner, 2017.
We have added a comparison of our results and the thinning rates from Walker and Gardner, 2017 to the Discussion section: However, we do not compare ice thinning rates with those of Zhao et al., 2017, since the time intervals they used for computing elevation change differ from ours.

P10, L1-3: The "We extracted" part of the statement should explicitly refer to Fig. 6S, and the location of the four profiles should refer to Fig. 6.
We have changed the section into:
We extracted data of surface velocities, TDX/TSX 2011–2014 elevation change rates, bedrock topography along four profiles on Airy and Fleming Glacier in order to estimate the recent and the grounding line location in 2008 after the first acceleration phase (Fig. S6 a-d). The location of the profiles as well as the deduced grounding line positions are shown in Fig. 6.

P10, L3-4: For "The plots", you mean Fig. 6 or Fig. S6? It would be clearer to say "Those profile plots (Fig S6 1-4) suggest . . .". Which glacier or profile are you talking about for the 2008 grounding line position?
We mean Fig. S6 1-4. We have changed this in the text accordingly.

P10, L5-6: "possible" and "likely" are same to me. It's not clear how the grounding line positions in 2008 are decided on Profile 2, 3, and 4.
The sentence has been removed during rewriting of the results section (5.3). We have changed the term "possible" to "tentative" making clear that the 2008 grounding line position is only a rough estimate. We have added more information on how the 2008 grounding line positions were deduced from the profiles to Sect. 4.3, 5.3 and Fig. S6 a-d.

P10, L7-15: Is detailed discussion of a supplementary figure in the main text proper? Consider including Fig. S6-3.
We agree with the reviewer. We have removed the section during rewriting of the results section (5.3). We hence have kept the Figure S6 c in the supplemental material.

P10, L18-20: About "no significant acceleration since 1996 . . .", if you compare the velocity at three sites with the 2015 velocity from Walker and Gardner, 2017, you will find some speed up from 1996 to 2015. Alternatively you need to qualify with "by 2013".
We have changed the section into:
The remarkable median speedup of ~1.3 m d^{-1} which we recorded between 2007 and 2011 is in good agreement with an acceleration of ~ 400–500 m a^{-1} reported by Walker and Gardner (2017) and Zhao et al. (2017) for the period 2008–2015. However, a comparison of our velocities in 2013 with their velocities in 2015 at the three measuring sites of Doake (1975) ~50 km upstream suggests that the recent speedup had not propagated up to these locations prior to 2015.

P10, L27-28: Besides the surface melt, basal melting water generated from the basal frication heating could be another trigger of enhanced basal sliding. It's hard to rule out the possibility of enhanced basal sliding unless you have further evidence.
We agree that liquid water generated from fricational heat can enhance basal sliding. Basal frication heat can increase if the glacier accelerates or if it gains mass. Hence, increased fricational heat is more likely a result of the acceleration, rather than the trigger of it. However, we do not want to rule out that in areas where the glacier is currently grounded, as a consequence of initial acceleration, basal sliding is enhanced due to melt water from increased fricational heat.
We have changed the section into:

All in all, enhanced basal sliding due to percolating meltwater is likely not the explanation for the observed increase in flow velocities. However, we do not rule out that as a consequence of the acceleration, basal sliding had increased in grounded areas by liquid water generated from greater basal frictional heat.

P10, L30-31: If this is your method to decide the grounding line position from the velocity data, please move this sentence to Sect. 4.3.
We have moved and reformulated the sentence (see answer P7, L22-23)

P11, L12: Please cite references for the Twaites Glacier and the Pine Island Bay.
We have added a reference to Rignot et al. (2014).

P24, L4: Modify “Linens” to “Lines”.
We have changed this.

Supplement Material

It is better to use consistent zero distance mark for the various profiles in both the main text (Fig. 2, 3, 5, 6) and the supplementary material (Fig. S6). The use of different starting points (the 1996 grounding line position or the 2007 ice front position) for describing the distance is confusing. If it is too difficult to shift the origin in the supplementary figures, the GL96 grounding line needs to be clearly marked.
We thank the reviewer for the helpful suggestion. We have changed the profile extent to the 1996 grounding line in Fig. S6.

P12: Modify the legend of a) and b) from “Ice Surface/Bottom elevation (OIB)” to “Ice Surface/Bottom elevation (PIB)”.
We have changed the legend accordingly.

P15, L3: Modify “profiles 1-5” to “profiles 1-4”. Also consider labeling figure parts as S6.a-d for consistency with other sections. Anyway add labels to the profile figures.
We have changed the labelling to S6.a-d and have modified the references in the text accordingly.

P15, L4: Can’t find OIB ice surface/bottom in those figures.
We have deleted the corresponding sentence.

P15, L5: Modify “grounding line” to “GL”.
We have changed this accordingly.

P15, L6-7: Can’t find Green, Red and Blue lines in those figures.
The sentence has been deleted.

P16, L7-8: It’s hard to tell the 2008 grounding line position upstream the 2011 front without direct evidence. Please explain it.
We agree with the reviewer that it is difficult to tell the exact 2008 grounding line position from the modelled bedrock data only. The only thing which is clear is that the grounding line must have been upstream of its 1996 position in 2008, since in 2008 the glacier front had retreated behind the 1996 grounding line location. The position which we state is only a best guess based on the data we have in hand. We hope that we have made this clearer in the rewritten text to Fig. S6 b and in the results section. We have also pointed to the limitations of the bedrock data in the text and have labelled the 2008 position in Fig. S6 b with a question mark.

P16, L10-11: Please add GL11 in Fig. S6.2.
We have added the GL11 to Fig. S6 b.

P17, L3: Move “in 2008” after “the grounding line”.
We have changed this accordingly.

P17, L5-6: Along Profile2, it’s hard to tell this hill in Fig. 6. Considering the uncertainty of bedrock ïij´Lyellow and brown line in Fig. S6.3), is it possible that this smaller hill is not physically real? On P18, L5-6 you suggest that “the topography may be distorted in the modelled bedrock data”.
Same answer as for P16, L7-8

References

Cook, A. J., Murray, T., Luckman, A., Vaughan, D. G. and Barrand, N. E.: A new 100-m Digital Elevation Model of the Antarctic Peninsula derived from ASTER Global DEM: methods and accuracy assessment, Earth Syst. Sci. Data, 4, 129–142, doi: 10.5194/essd-4-129-2012.

Depoorter, M. A., Bamber, J. L., Griggs, J. A., Lenaerts, J T M, Ligtenberg, S R M, van den Broeke, M R and Moholdt, G.: Calving fluxes and basal melt rates of Antarctic ice shelves, Nature, 502, 89–92, doi: 10.1038/nature12567.

Doake, C. S. M. and Vaughan, D. G.: Rapid disintegration of the Wordie Ice Shelf in response to atmospheric warming, Nature, 350, 328–330, doi: 10.1038/350328a0.

Reynolds, J. M.: The structure of Wordie ice shelf, Antarctic peninsula, Bulletin-British Antarctic Survey, 57–64.

Rignot, E., Jacobs, S., Mouginot, J. and Scheuchl, B.: Ice-shelf melting around Antarctica, Science (New York, N.Y.), 341, 266–270, doi: 10.1126/science.1235798.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H. and Scheuchl, B.: Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011, Geophys. Res. Lett., 41, 3502–3509, doi: 10.1002/2014GL060140.

Rignot, E., Mouginot, J. and Scheuchl, B.: Ice flow of the Antarctic ice sheet, Science (New York, N.Y.), 333, 1427–1430, doi: 10.1126/science.1208336.

Rignot, E., Vaughan, D. G., Schmeltz, M., Dupont, T. and MacAyeal, D.: Acceleration of Pine Island and Thwaites Glaciers, West Antarctica, Annals of Glaciology, 34, 189–194, doi: 10.3189/172756402781817950.

Schoof, C.: Ice sheet grounding line dynamics. Steady states, stability, and hysteresis, J. Geophys. Res., 112, 1720, doi: 10.1029/2006JF000664.

Stearns, L. A.: Outlet glacier dynamics in East Greenland and East Antarctica, Ph.D. thesis, Univ. of Maine, Orono, 2007.

Stearns, L. A.: Dynamics and mass balance of four large East Antarctic outlet glaciers, Ann. Glaciol., 52, 116–126, doi: 10.3189/172756411799096187.

Vaughan, D. G.: Implications of the break-up of Wordie Ice Shelf, Antarctica for sea level, Antarctic Science, 5, doi: 10.1017/S0954102093000537.

Vaughan, D. G. and Doake, C. S. M.: Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula, Nature, 379, 328–331, doi: 10.1038/379328a0.

Walker, C. C. and Gardner, A. S.: Rapid drawdown of Antarctica's Wordie Ice Shelf glaciers in response to ENSO/Southern Annular Mode-driven warming in the Southern Ocean, Earth and Planetary Science Letters, 476, 100–110, doi: 10.1016/j.epsl.2017.08.005.

Zhao, C., King, M. A., Watson, C. S., Barletta, V. R., Bordoni, A., Dell, M. and Whitehouse, P. L.: Rapid ice unloading in the Fleming Glacier region, southern Antarctic Peninsula, and its effect on bedrock uplift rates, Earth and Planetary Science Letters, 473, 164–176, doi: 10.1016/j.epsl.2017.06.002.