Marie Byrd Land glacier change driven by inter-decadal climate-ocean variability: Author response to reviews

Dear Dr. Wouters (Editor),

We thank all three reviewers for their insightful comments and feedback which have helped us to clarify our manuscript. In the following response document, we have compiled and numbered each of the reviewer's comments (*blue italics*), and include our response (black text) and amendments to the original text (*grey italics*). Page/line numbers refer to the original manuscript published on 29th January 2018 at: *https://www.the-cryosphere-discuss.net/tc-2017-263/tc-2017-263.pdf*.

We hope that you will find our amendments to the manuscript satisfactory for publication in TC, and we look forward to hearing from you soon.

Kind Regards,

Frazer
(on behalf of all co-authors)

Reviewer 1

1. *"The authors analyzed the glacier changes in Marie Byrd Land sector for the past 20 years. Using ICESat and CryoSat-2, they show that grounding line retreat reduced by 68% in CryoSat-2 era, which is caused by oceanic forcing. Although slowdown of grounding line retreat is an interesting and important finding, their argument that observed changes are caused by "reduced Ekman upwelling on and around the continental shelf" is not well supported. I recommend major revision. Very nice results, but some interpretations seem to me rather too speculative. More analyses and/or different interpretations are required".*

   We are grateful to the reviewer for his/her interest in our work, and address his/her concerns regarding the need for a major revision in the following section.

Major comment:

2. *"Very good job listing oceanic processes, which may impact the glacier retreat. Although authors are aware of many oceanic processes, authors conclude that "during weaker offshore winds relative to the ICESat era reduced Ekman upwelling on and around the continental shelf, resulting in a decline in Circumpolar Deep Water intrusion to the sub Getz ice-shelf cavity", which is not supported from any of the analyses conducted in the paper".*

   "As authors are aware, oceanic conditions (e.g., large and small scale circulations, bathymetry, stratification, etc) are very much different in the Marie Byrd Land sector. Since there are many processes potentially controlling potential temperature in the ice shelf cavity and thus ice shelf melt rates and relative importance of these processes are likely regionally different, authors are not able to conclude that "reduced Ekman upwelling on and around the continental shelf" is the key process for this region, just based on the fact that they observe changes in Ekman upwelling. Cited papers such as Steig et al., 2012, Dutrieux 2014, and St. Laurent et al., 2016 have conducted data analysis and/or modeling. Further analysis including data analysis and modeling is likely required to claim that "reduced Ekman upwelling on and around the continental shelf" is the reason for the observed changes".

   As the reviewer suggests, this study builds upon the work of -in particular- Thoma et al. (2008), Steig et al. (2012), Jacobs et al. (2013) and Dutrieux et al. (2014), who used a combination of ocean modelling (adapted to include sub-ice-shelf cavity bathymetry after Holland and Jenkins (2001); Thoma, Steig), atmospheric reanalysis data (Thoma, Steig, Dutrieux, Jacobs) and/or in-situ ocean observations (Dutrieux, Jacobs) to examine inter-annual-scale changes in oceanic forcing of the glaciers draining the Marie Byrd Land (Getz) and Amundsen Sectors.

   In this contribution, we have reported on temporal changes in 10 m zonal wind and Ekman vertical velocities near to the continental-shelf break between 2003 and 2015, using virtually identical calculations to those employed by Steig/Dutrieux/Jacobs, and more recently by Greene et al. (2017) and Walker et al. (2017). These calculations have previously been shown to be highly correlated to both observed and modelled changes in the hydrography of the sub-shelf cavity (Dutrieux, Jacobs), thus we believe our estimates provide a reliable first-order proxy for the state of the ocean underneath Getz Ice Shelf between 2003 and 2015.

   Whilst we fully agree that the local-to-large-scale processes controlling sub-cavity CDW availability are undoubtedly more complex than those captured by these simple diagnostic calculations (see the discussion in Section 4.2.1; also Webber et al. (2017) referenced therein), it is important to note that the ability to carry out in-situ-derived data analyses or observationally-constrained ocean-modelling experiments over our study domain is currently limited owing to an almost complete dearth of either spatially or temporally continuous oceanic data during our observational window. To our knowledge, the most continuous spatial-temporal CTD observations along the length of Getz Ice Shelf were last acquired in 2000 and 2007, as reported in Jacobs et al. (2013). Jacobs et al. (2013) document a much increased oceanic forcing and observed melt rate of Getz in 2007, believed to be driven by an enhanced Ekman transport relative to 1999/2000 (i.e. reduced upwelling/CDW presence in 1999/2000, increased upwelling/CDW presence in 2007). Within the neighbouring and much more densely surveyed Amundsen Sea Embayment, Dutrieux et al. (2014) attributed the dramatic cooling of Pine Island Bay in recent years to a marked suppression of zonal wind stress (and by implication, Ekman upwelling) at the continental-shelf break around ~2011-2012. Resulting in a much-reduced thermocline and on-shelf CDW presence until at least 2014 (Webber et al., 2017), these changes and those of Jacobs et al. (2013) are fully consistent with our 1979-2017 time-series of *wE* shown in Figure 4 (b), which we believe act as important independent verifications of our MBLS calculations.

To further support our use of zonal wind/*wE* in the manuscript, we examined changes in the vertical hydrography of Getz' continental shelf and break, using the Met Office EN4 objective analysis solution for 2000-2017 (Figure 1 of this response document). Unlike ocean models or reanalysis data, this product is a monthly gridded interpolation of all available in-situ ocean observations derived from the World Ocean Database (WOD09/13) and other data sources (see Good et al. (2013) for further information). Whilst subject to high uncertainty bounds and coarse (1°) spatial resolution (Good et al., 2013), this result shows a clear reduction in thermocline depth between 2010-2015 relative to 2003-2008, with unprecedented deepening between 2013 and 2015. Following Dutrieux et al. (2014), a less significant yet clear decrease in thermocline depth is also witnessed c.2011-2012, as is a shallower thermocline in 2007 compared to year 2000 in accordance with the findings of Jacobs et al. (2013). These patterns are all consistent with the patterns of change shown in our manuscript's Figure 4 (b), and hence bolster our confidence in the ability of *wE* to act as a reliable indicator for the changing oceanic conditions near and underneath Getz Ice Shelf during 2003-2015.

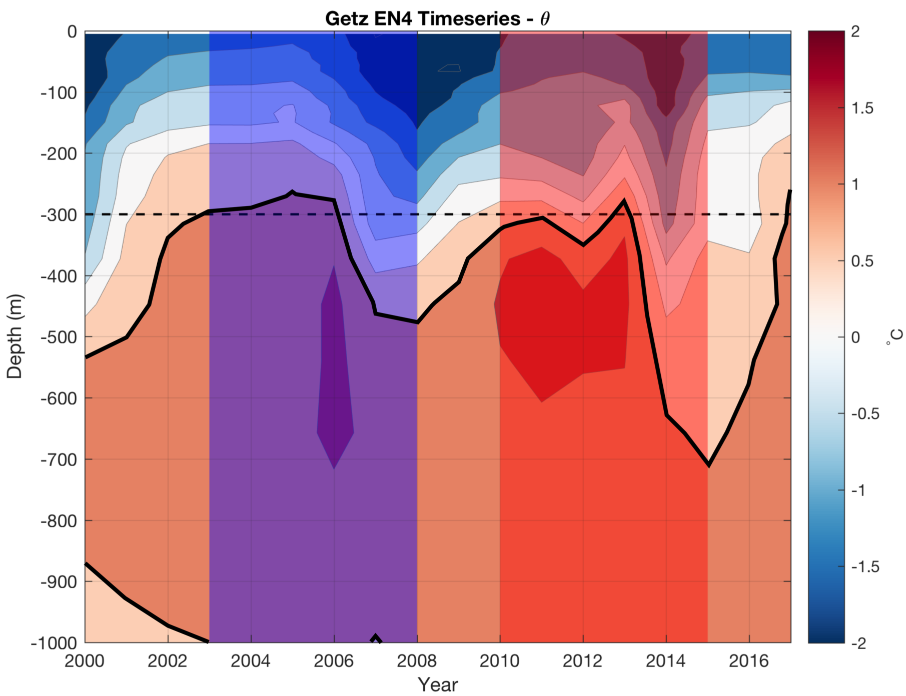

Figure 1: Met Office EN4 objective analyses (potential temperature; °C) of the Getz region, derived from all model grid cells contained on the shelf and shelf break. Semi-transparent blue and red hatches denote the ICESat (2003-2008) and CryoSat-2 (2010-2015) observational periods (cf. Figure 4; main manuscript); thick black line denotes the +1°C isotherm ≈ the limits of the mCDW/CDW layer (cf. Jacobs et al., 2013). Dashed black line signifies the -300 m depth contour for reference.

There is one caveat to this EN4 analysis: the dense observational datasets acquired over the Amundsen Sea Embayment and Getz regions in recent years (e.g. Wåhlin et al., 2010; Jacobs et al., 2013; Dutrieux et al., 2014; Webber et al., 2017) may not be fully assimilated into this dataset. For this reason we present the EN4 analysis only in this response, rather than proposing its inclusion in the main text.

Author amendments to manuscript:
In summary of the above, we believe we are justified to use wind/Ekman anomalies in the manuscript as proxies for oceanic forcing of changes to the hydrography of Getz' sub-shelf cavity through time. Except for the coarse EN4 interpolation undertaken for this response (Figure 1), the dearth of continuous in-situ data collected near Getz Ice Shelf over the study period of 2003-2015 preclude further meaningful data analyses or modelling that the reviewer advocates.

That said, we fully agree with the reviewer that our calculations are a simplification of the undoubtedly complex range of processes controlling Getz' hydrography, and have clarified this point and justified our chosen methodology throughout the manuscript. Specifically:

i) The abstract has been rewritten to emphasise the importance of bed topography and the more complex ice-sheet ocean interactions likely at work. (Latter section of abstract now reads: "*Along Getz Ice Shelf, grounding-line retreat reduced by 68% during the CryoSat-2 era relative to earlier observations. Climate reanalysis data reveal that wind-driven upwelling of Circumpolar Deep Water would have been reduced during this later period, suggesting that the observed slowdown was a response to reduced oceanic forcing. However, lack of comprehensive oceanographic and bathymetric information proximal to Getz Ice Shelf's grounding zone make it difficult to assess the role of intrinsic glacier dynamics, or more complex ice-sheet-ocean interactions, in moderating this slowdown. Collectively, our findings underscore the importance of spatial and inter-decadal variability in atmosphere and ocean interactions in moderating glaciological change around Antarctica*").

ii) Section 2.3 has been modified to justify our choice of methods owing to the lack of observational data acquired over the MBLS during the 2003-2015 period (Paragraph now reads: "*To investigate the role of atmospheric and oceanic forcing on glaciological change between 2003 and 2015, we examined mean zonal wind and Ekman vertical velocity anomalies on and near the MBLS' continental shelf, using ECMWF ERA-Interim climate reanalysis data (cf. Dee et al., 2011). These methods were utilised due to a dearth of spatially and temporally continuous in-situ oceanographical observations within the MBLS during the observational period, with the last comprehensive and publically-available surveys having been carried out in 2000 and 2007 (Jacobs et al., 2013)*").

iii) Section 2.3.2. (Page 6, Line 19) has been reworded to re-emphasise that these calculations offer a first-order proxy for changes in Ekman transport-induced upwelling onto the continental shelf.
(Paragraph now reads: "*A derivative of the wind stress field, Ekman vertical velocity, approximates the rate at which the wind stress curl raises subsurface isopycnals, and can be used as a first-order estimate for Ekman transport-induced upwelling of interior ocean water masses, including relatively warm upper CDW layers (Marshall & Plumb, 2008)"*).

iv) The discussion in 4.2.1 (Page 12, Line 5-6) has been extended to assert the importance of acquiring observational data at/near Getz Ice Shelf in the coming years, to improve our understanding of the processes controlling change within Getz' sub-shelf cavity.
(Section now reads: *"Our findings underscore the potential importance of inter-decadal variability in both regional- and local-scale atmosphere and ocean interactions in moderating glaciological change along this sector of Antarctica (Fig. 6). Our observations also highlight the need for continuous in-situ ocean observations near and underneath Getz Ice Shelf in the future. Such observations would yield greater insight into the specific oceanographic mechanisms controlling the hydrography of Getz Ice Shelf's sub-shelf cavity (cf. Jacobs et al., 2013; Kim et al, 2017; Webber et al., 2017), beyond the approximations presented here and the spatially and temporally-limited observations previously reported (e.g. Wåhlin et al., 2010; Jacobs et al., 2013)…".*

v) In relation to i)-iv) above, the manuscript's conclusion has been reworded to reemphasise the complexity of the ocean interactions causing changes to the Getz sub-shelf cavity, and includes an explicit statement on the requirement for continuous ocean survey in the future (Page 15 Lines 21 to Page 16 Line 11).

Specifically, paragraph 2 now reads: "*We find a correspondence between the observed slowdown in Getz Ice Shelf's grounding-line retreat and a reduction in external atmosphere-ocean forcing as inferred from climate reanalysis data. During the CryoSat-2 era, weaker offshore winds relative to the ICESat era reduced Ekman upwelling on and around the continental shelf, resulting in a likely decline in Circumpolar Deep Water intrusion to the sub-Getz ice-shelf cavity. This is analogous to observed changes elsewhere in the Amundsen Sea Sector since 2009 (Dutrieux et al., 2014, following Steig et al., 2012; Turner et al., 2017), and is supported by empirically-constrained trends of oceanographic change observed near Getz Ice Shelf's calving fronts in the years immediately preceding the ICESat era (Jacobs et al., 2013). However, at the local scale, grounding zone bed geometry, which is poorly constrained along much of Getz Ice Shelf, may have also played a role in modulating retreat rates. Additional near-shore ocean processes, such as eddy-mediated transport of CDW across the shelf break (Stewart & Thompson, 2015), seasonal variations in on-shelf heat transport linked to local-scale atmospheric forcing (Webber et al., 2017) and the influence of sea ice on Ekman vertical velocities (Kim et al., 2017), may also have contributed to the observed reduction in GL retreat*".

Paragraph 4 now reads: "*Collectively, our findings from the Marie Byrd Land Sector underscore the importance of both spatial and inter-decadal variability in ocean and atmosphere interactions for moderating glaciological change around Antarctica. To assess the importance of these interactions, increased spatial-temporal oceanographical observations and high-resolution geophysical measurements of the MBLS' geological setting are required*".

3. *The title of this paper indicates that glacier change is driven by inter-decadal climate ocean variability, which is misleading. Authors do not show that the impact of other processes are small. There are other processes impacting glacier retreat (section 4.2) and these processes may possibly be more important (e.g., subsection 4.2.3)".*

The reviewer acknowledges that we have detailed other possible influences on MBLS glacial change in our paper. To acknowledge the concern that the paper's title conveys too much certainty that the observed glacial changes are driven exclusively from the atmosphere/ocean, we have amended the manuscript title to the following, which we believe also addresses the comments from Reviewers #2 (Comment 1) and #3 (Comments 2 and 3).

"*Glacier change along West Antarctica's Marie Byrd Land Sector and links to inter-decadal atmosphere-ocean variability*".

Minor comments

4. *"Page 9 Lines 14-25: It is clearer if authors can show spatial pattern of vertical Ekman velocity for each era (not just the difference as in Figure 5)".*

   Figure 5 now shows three subplots showing *wE* for (Jan) 2003 to (Jan) 2008 (a), (Jan) 2010 to (Dec) 2013 (b), and their difference (c). The figure caption has been reworded to reflect this change, along with several references to the new subplots in Sections 3.4 (Page 9 Lines 26-31) and 4.2.1 (Page 11 Line 26; Page 12 Line 3).

5. *"Page 11 Lines 10-11: Even if it is fully synchronous, it is not convincing that "reduced Ekman upwelling on and around the continental shelf" changes the oceanic condition in the ice shelf cavity, reduces the melt rates, and slows down the grounding line retreat. As stated above, there are many processes and further analyses are required".*

   We interpret this as essentially the same comment to which we have responded to the reviewer's comment 1 above.

6. *"Page 11 Lines 23-27: Where do you mean? Is there different polynya in near Getz region? If so, are these responding similarly to the Amundsen Sea polynya?"*

   This statement refers to the area of deep downwelling centred immediately north of Dotson Ice Shelf's calving front at ~115° W, which extends over the eastern and central tributaries of the Getz-Dotson Trough as seen in Figure 5. This area resides over the Amundsen Sector's largest polynya, commonly referred to in the literature as the 'Amundsen Sea Polynya' (cf. Nihashi & Ohshima, 2015; 2017; Kim et al., 2017).

7. *"Page 14 Lines 10-29: "These longitudinal limits corresponds broadly with . . . Getz Ice Shelf". These argument seems speculative. Need more clarification".*

   We are unsure why the reviewer finds this statement speculative, as the mean slope front identified by Whitworth et al. (1998) and Lee & Coward (2003) commences westward towards the Ross Sea at ~120° W and ~125-135° W, respectively, which is generally consistent with the regionally-contrasting glaciological behaviour (both GL retreat and ice surface elevation change rates) we observe at and west of Getz Ice Shelf. Representing a non-stationary, semi-permanent feature, the precise longitudinal limits of the ASF wax and wane and are controlled by a multitude of oceanic processes (cf. Jacobs et al., 1991; Baines et al., 2009).

8. *"Page 15 Lines 22-Page 16 Line 12: See major comments #1 and #2".*

   This comment refers to the reviewer's comments 2 and 3 according to our notation, which we have addressed above.

9. *“Figure 6: This seems to be not accurate. Should circulation off the Marie Byrd Land sector be influenced by the Ross Gyre and CDW circulation be opposite?”*
For simplicity, we originally did not include the influence of the Ross Gyre in Figure 6 owing to its non-stationary position through time. However, as the reviewer suggests, the presence of the Ross Gyre, which may intermittently encroach as far east as the Amundsen and Bellingshausen Sea regions (Assmann & Timmerman, 2005; Jacobs et al., 2013), may indeed influence the circulation of CDW along the MBLS coast. Therefore, we have decided to make reference to this phenomenon in the updated version of the manuscript.

To examine the influence of the Ross Gyre on the Marie Byrd Land Sector, we examined the vertical hydrography of the MBLS' coastline using the Met Office EN4 objective analysis product detailed in our response to comment ‘2’ above. This was done by examining annually-averaged potential temperatures along the region west of 135° W (Figure 2), in comparison to the Getz–only region shown in Figure 1. Relative to Figure 1 (Getz), Figure 2 shows high temporal variability in 1°C thermocline depth and thickness of the warm (>1°C) ocean layer, in addition to a notable deepening of the shallower, colder (<0.5°C) waters. Consistent with vertical mixing or other oceanic processes associated with periodic incursions of the Ross Gyre, such an incursion may partly explain the deep downwelling centred at ~140° W during 2010-2015 (new Fig. 5b and c in main text), and implies a maximum easternmost boundary of ~129° W over our observational period.

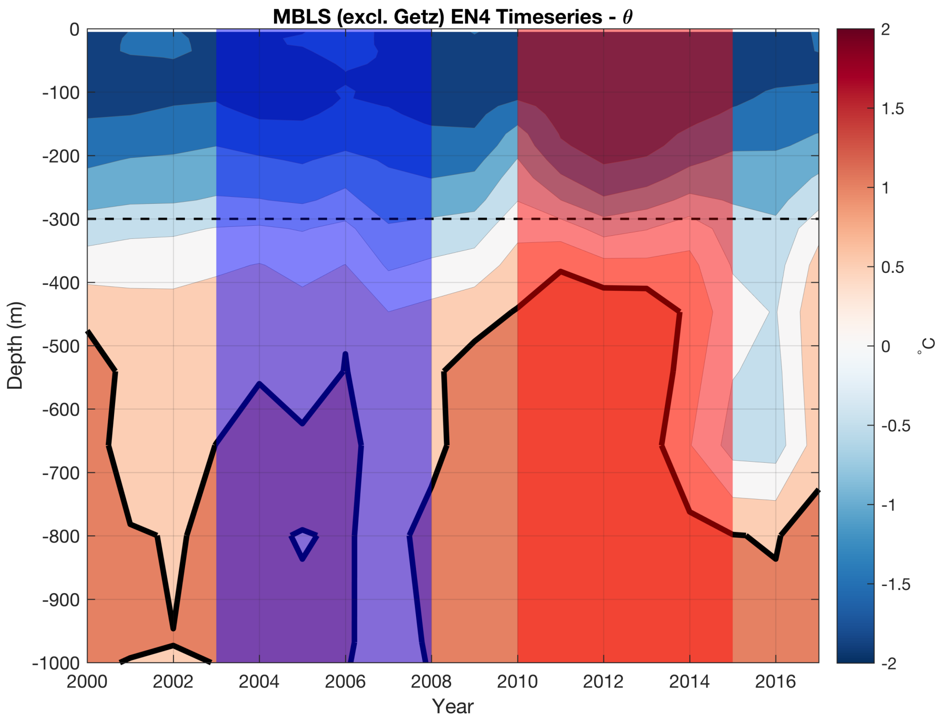

Figure 2. Same as Figure 1 but for the region west of 135° W, derived from all model grid cells contained on the shelf and shelf break. Semi-transparent blue and red hatches denote the ICESat (2003-2008) and CryoSat-2 (2010-2015) observational periods (cf. Figure 4; main manuscript); thick black line denotes the +1°C isotherm ≈ the limits of the mCDW/CDW layer (cf. Jacobs et al., 2013). Dashed black line signifies the -300 m depth contour for reference.

To reflect the above, we have adapted Figure 6 of our manuscript to include the influence of the Ross Gyre in the region west of Getz (Figure 6 (b)). As the reviewer suggests, this now shows a reversal and cooling and/or downwelling of the ACC-derived CDW layer towards the Ross Sea.

In addition to this amendment, the following edits have been made to the main text and caption of Figure 6:

Page 15 Line 1: Sentence now reads: *"Influenced by the position of the Ross Gyre (Assmann & Timmerman, 2005), this ACC behaviour persists…."*.

Page 34 Line 3: Sentence now reads: *"The northward deflection of the ACC, influenced by the easternmost limits of the Ross Gyre, also minimises the presence of CDW near the shelf slope"*.

Reviewer #2

"The authors present an analysis of changes in grounding line position for the Marie Byrd Land Sector using a well established method of detecting the break in slope from satellite remote sensing imagery (Landsat & ASTER). Over the 2003 - 2015 period they find that 33% of the grounding line underwent retreat, with the greatest rates found over the Getz Ice Shelf grounding line region. These results are consistent with the ice shelf thinning rates presented in the paper and previous studies in the literature. In addition, they conclude that the variations in retreat rate between the ICESat and CryoSat-2 era are due to inter-decadal changes in ocean forcing.

The paper is well written and (as the authors state) provide much needed insights on a region of West Antarctica that has previously suffered from limited observations. The sectors increasing contribution to the total Antarctic mass loss make these findings particularly relevant to the community and therefore appropriate for publication in TC. I believe however there are some points that need addressing, particularly in the discussion of their findings before it can be accepted for publication. These are outlined below."

We are grateful to the reviewer for his/her thorough review of our manuscript and his/her insights.

General Comments

1. *"The title and the main arguments in the paper suggest the primary driver of change in the region is due to an inter-decadal climate-ocean variability. Whilst evidence of this is provided in the text to support this, it seems to give the impression that it is the sole dominant driver of change in the region. The text also states other factors such as geological controls and the effect of increased basal melt from neighbouring ice shelves on modifying the CDW. Unless it can be quantitatively proved that the impacts of these are minimal compared to the climate-ocean variability, then I think the emphasis placed on this sole factor needs to be better balanced with other potential drivers. I would also suggest revising the title to reflect this".*

   This comment echoes that of Reviewer# 1 and our actions in response are detailed in our response to Reviewer #1's comment 3) above.

2. *"In the method section detailing the Swath SARIn processing of CryoSat-2 data and subsequent dh/dt calculations, it is stated that the plane fit following McMillan et al (2014) was used (P5, L18). This plane fitting approach was applied to POCA data and therefore includes a coefficient to account for firn penetration of the altimeter from ascending and descending passes (Supplementary material equation 1, McMillan et al 2014). As the Swath SARIn processing chain differs, is this approach still applicable? If the plane fit equation used in this instance differs from that in the McMillan paper, then it should be included in the main text (or as part of the supplementary information)".*

   The reference to McMillan et al. (2014) was intended as a general reference to the plane fit approach as opposed to cross-over or repeat track techniques. However, we understand that this may lead to ambiguity as this specific aspect of the 'McMillan' inversion was not applied to our dataset (since swath data have an inherently different power structure to that of Point of Closest Approach (POCA) returns). To avoid this ambiguity, we now refer to Gourmelen et al. (2017b) when describing the plane fit solution on Page 5 Line 18. Sentence now reads: "*We derived linear rates of surface elevation change from time-dependent swath elevation data acquired between 2010 and 2016 using a plane fit approach on a 10 km grid posting (cf. Gourmelen et al., 2017b)*".

We have additionally amended all reference to Gourmelen et al. (2017) to "*Gourmelen et al. (2017a)*" in light of this amendment, and added Gourmelen et al. (2017b) to the reference list.

Technical Corrections

3. *"P1 L26 - "Projecting contributions" I would rephrase this to something like "accurately projecting the contribution of the West Antarctic Ice Sheet to global sea level rise"".*

   Page 1 Line 26: Sentence now reads: "*Comprehending the drivers of these ice losses is imperative for accurately projecting the contribution of the West Antarctic Ice Sheet to global sea level rise in the coming decades (e.g., Vaughan et al., 2013)*".

4. *"P1, L25 - An extra reference should be added here as ice mass losses over the ASE have been measured from multiple techniques, not just the mass budget/IOM method. I would recommend adding Sutterley et al (2014), which shows mass losses over the region from separate techniques since 1992".*

   Reference added to text and reference list.

5. *"P1 L29 & L30 - Would it not be appropriate to put the Paolo et al (2015) reference with those regarding ice shelf melting as opposed to inland dynamic thinning?"*

   Yes – thanks for pointing out our error here.

6. *"P3, L17 - "Final Ib products were smoothed using standard GIS tools" - The specific tool or method should be stated for reproducibility purposes. Do the smoothing processes used change the position of the grounding line? Or is the extent of movement caused by this tool below the resolution for which the grounding line can be detected from Landsat 7/8 or ASTER?"*

   We used a Polynomial Approximation with Exponential Kernel (PAEK) algorithm to smooth the I_b products under a user-defined forward-looking tolerance limit, following Depoorter et al. (2013). For clarity here, a tolerance threshold of 500 m was chosen to smooth our I_b products, which resulted in minimal changes in the position of the picked GL (generally at the sub-pixel scale). As the reviewer surmised, these modifications lie well below the resolution in which the GL could be detected from Landsat/ASTER, so are assumed to be negligible. This procedure has been detailed in Depoorter et al. (2013) as well as in the recently published technical metadata of Christie et al. (2018), which we have added to the paper's reference list and data availability section. We have therefore restructured the sentence to include these two references. Sentence now reads: "*The final I_b products were smoothed using standard GIS tools (cf. Depoorter et al., 2013; Christie et al., 2018), and reflect the mean summertime GL position for each year as resolved from all available Landsat or ASTER imagery*".

7. *"P 10 L29 - P11 L2 - Is there any way to quantify this or explore this in more detail? As this implies that whilst the ocean-climate forcing is a major driver, at the local scale other factors could play a governing role in the rate of grounding line change".*

   This section was simply intended to act as a transition to the following more detailed discussion rather than to act as standalone text. More thorough discussion of the constraints on glaciological change along this part of the ice shelf is presented in Sections 4.2-4.24. To clarify this purpose, we have added reference to the immediately following discussion section in the main text. This section now reads: "*Collectively, these observations imply that local-scale ice-ocean processes or geological configurations underneath the most easterly portion of Getz Ice Shelf may render the region relatively immune to ocean-forced dynamic thinning and subsequent GL retreat. These considerations are discussed in further detail next (Section 4.2)*".

8. *"P11 L13-15 - A recently published paper by Paolo et al (2018) looks at the impact of ENSO forcing on the West Antarctic Ice Shelves and seems to support your suggestions, so may be useful to add a reference to it here".*

   This paper was not published when we submitted this manuscript but it certainly does support our work. We have reworked the closing sentence of this paragraph to incorporate the citation, and added Paolo et al. (2018) to the reference list. Sentence (Page 11 Line 15-17) now reads: "*This hypothesis concurs with the recent findings of Paolo et al. (2018) who examined the response of ENSO variability on all Pacific-facing ice shelves over the radar altimetry record (1994-2017), as well as the earlier findings of Jacobs et al. (2013), who attributed a reduced thermocline and glaciological forcing along Getz Ice Shelf in the years preceding the ICESat era to a strong La Niña event circa. 2000*".

9. *"P15 L15-20 - This seems to suggest that inter-decadal climate-ocean variability is perhaps not the sole driver of change in this region. Is it possible to expand this discussion or quantify this effect? Otherwise a change of emphasis may be necessary to encompass these varying effects (see general comments above)".*

   See our response to this Reviewer's Comment 1 and in turn our response to Reviewer #1 Comment 3. The point is well raised and accepted.

10. *"P15 L28-L29 - I don't think this statement can be made without quantitative analysis of other factors (as discussed above). I think this should be reworded to encompass this explanation is part of variety of factors affecting the Getz (particularly at the local scale)".*

    Also addressed in our response to this Reviewer's Comment 1 and in turn our response to Reviewer #1 Comment 3 above.

11. *"P17 L10 - I would rephrase "RACMO2 and IMAU-FDM models used in the CryoSat-2 swath processing chain" as the models are not used in the generation of the swath data itself, but in determining ice shelf dh/dt".*

    Thanks – we have replaced the word "swath" here with "*Δh/Δt*".

12. *"P19 L15 - Fretwell et al reference does not list all paper authors".*
13. *"P23 L11 - Shepherd et al reference does not list all paper authors".*

    Both changed to include full author lists.

14. *"Figure 1 - The scale bar in the bottom right hand corner is difficult to read against the background colour scheme, I would suggest changing it another colour (perhaps white)".*

Scale bar changed to white.

15. *"Figure S1 - A scale bar should be added to this plot. In addition, I would suggest changing the ice shelf front position colour/line to make it more prominent compared to the grounding line delineation".*

    Scale bar added, and we have changed the colour and thickness of the ice shelf fronts to add greater contrast against the delineated GLs.

16. *"Figure S5 - The jet colour bar on this figure should be changed to avoid readability issues. This colour bar also clashes with the contour lines, making them difficult to view. The contour lines however could be kept as is, depending on choice of new colour table. Additionally, the colour bar needs to have a label stating what it is representing and the units".*

    We have redesigned Figure S5 to incorporate a new colour map as the reviewer suggested, and have added in the colour legend. We have also changed the colour of the contours to ease readability.

Reviewer #3

"In this manuscript Christie and colleagues compare a newly developed product of grounding-line migration along the Marie Byrd Land sector with changes in surface elevation and discuss possible ocean forcing of the observed changes. My limited knowledge doesn't allow me to comment on the quality of these products or on the method used to obtain them. However, I enjoyed reading the in depth analysis of possible ocean forcing and its mechanism. The authors computed the wind stress anomalies and the Ekman upwelling, looked at the configuration of the bottom topography, the location of the ACC and Antarctic slope current. This results in a very interesting investigation. However I think analysis could be made clearer. See here three examples to help doing it:"

We thank the reviewer for his/her kind words and interest in our manuscript, and address his/her suggested revisions below.

1. *"The issue of why 33% of the grounding line retreated over the full 2003-2015 period is not clear. This is reflected by the short and speculative section 4.1. I do not think this problem should be solved in this manuscript but a clear acknowledgment of the remaining unknowns seem necessary. Maybe stating clearly that the observation of long term grounding line retreat are probably linked to ocean forcing but this cannot be shown given the limited data available and the precise mechanism is unknown".*

   Section 4.1 was merely intended to build the foundations for the immediately following sections, which provide detailed discussion on the ocean and other mechanisms driving change (or lack thereof) throughout the MBLS. We have added a note to the section to this effect (see response to Reviewer #2, comment 7).

   It is important to note that whilst GL migration and ice-shelf thinning rates abated during 2010-2015 relative to 2003-2008 (Figs. 2 and 3), the observed changes during this epoch were still almost exclusively defined by GL retreat and negative ice-shelf thickness change (implying thinning) rates. This indicates that throughout 2003-2015 the region has been in a state of dynamical imbalance, even if the retreat has reduced in the later period.

   To add a little more clarity on this point we have reworded part of Section 4.2, paragraph 1 to mention explicitly the role of dynamic imbalance throughout the observational period. The paragraph (Page 10 Line 15-25) now reads: *"The most prominent GL retreat throughout the MBLS occurred along the ~650 km Getz Ice Shelf (Fig. 1; Sect. 3.1), which neighbours the recent, rapidly downwasting ice masses of the wider Amundsen Sea Sector. This was a likely consequence of the substantial thinning and basal melting witnessed over this region in recent decades, indicative of an ongoing dynamically-driven glaciological imbalance through time (Figs. 2 and 3; see also Pritchard et al., 2009; 2012; Jacobs et al., 2013; Paolo et al., 2015). Indeed, all GL retreat within the central and western sectors of Getz Ice Shelf occurred directly upstream of well-surveyed, deep (>400 m) bathymetric depressions north of the ice fronts (Fig. 1) …"*.

2. *"In 4.2.1 the fact that grounding line retreat slew down during the 2010-2015 period but the shelf continued to thin is discussed. At the end different hypothesis are made to explain this apparent contradiction: "Possible confounding factors are surface mass balance processes, grounding zone bed geometry, and local-scale changes in ice dynamics". These factors are discussed at length in the followinf sections so it would be interesting to have the answer to that contradiction in the conclusion".*

This comment closely echoes those made by Reviewer #1 (comments 3 and 9) and Reviewer #2 (comments 1, 9 and 10), which we have explicitly addressed in our responses above. This has involved the reworking of Section 5 to provide a more balanced discussion of the processes controlling the observed changes across Getz Ice Shelf and the wider-MBLS.

3. *"In 4.2.3 the authors say: "Until more comprehensive knowledge of Getz Ice Shelf's grounding zone bed structure exists, glacier/ice-stream- specific internal variability, moderated by bed conditions at the 2010-2015 grounding zone, cannot be reliably dismissed as an additional control on the slowdown of GL retreat rate during the CryoSat-2 era. " but then in the conclusion I read "We attribute the observed slowdown in Getz Ice Shelf's grounding-line retreat to a reduction in external climate-ocean forcing as inferred from climate reanalysis data. " This sounds contradictory, bed geometry might have played a role but the authors conclusion is still that ocean forcing is responsible for the slow down".*

   This is a further echo of Reviewer #1 comment 3 and Reviewer #2 comment 1, and has been actioned accordingly.

Minor comments:

4. *"The expression "climate-ocean" is strange, the ocean is part of the climate system, I think in most places it could be replaced by atmosphere-ocean or more explicitly "wind driven ocean"".*

   All instances of "climate-ocean" in the manuscript have been changed to "atmosphere-ocean".

5. *"p.1 l.15: "33% of the grounding line underwent retreat", how much underwent advance? It could help the reader by stating this here as well. I first thought this meant that 67% underwent advance".*

   We have extended this sentence (Page 1 Line 15) to read: "*During the observational period, 33% of the grounding line underwent retreat, with no significant advance recorded over the remainder of the ~2200 km long coastline*".

6. *"p.6, l.28: f is the Coriolis parameter not the variations in the Coriolis parameter".*

   Yes - we have reworded this sentence to read: "*where f denotes variations in the Coriolis parameter at latitude φ; ω is the Earth's angular velocity (7.292 × 10-5 rad s-1); and p_w is the density of the Ekman layer ocean water (1027.5 kg m-3)*".

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Glacier change along West Antarctica's Marie Byrd Land Sector and links to inter-decadal atmosphere-ocean variability

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Abstract. Over the past 20 years satellite remote sensing has captured significant downwasting of glaciers that drain the West Antarctic Ice Sheet into the ocean, particularly across the Amundsen Sea Sector. Along the neighbouring Marie Byrd Land Sector, situated west of Thwaites Glacier to Ross Ice Shelf, glaciological change has been only sparsely monitored. Here, we use optical satellite imagery to track grounding-line migration along the Marie Byrd Land Sector between 2003 and 2015, and compare observed changes with ICESat and CryoSat-2-derived surface elevation and thickness change records. During the observational period, 33% of the grounding line underwent retreat**, with no significant advance recorded over the remainder of the ~2200 km long coastline**. The greatest retreat rates were observed along the 650-km-long Getz Ice Shelf, further west of which only minor retreat occurred. The relative glaciological stability west of Getz Ice Shelf can be attributed to a divergence of the Antarctic Circumpolar Current from the continental-shelf break at 135° W, coincident with a transition in the morphology of the continental shelf. Along Getz Ice Shelf, grounding-line retreat reduced by 68% during the CryoSat-2 era relative to earlier observations. **Climate reanalysis data reveal that wind-driven upwelling of Circumpolar Deep Water would have been reduced during this later period, suggesting that the observed slowdown was a response to reduced oceanic forcing. However, lack of comprehensive oceanographic and bathymetric information proximal to Getz Ice Shelf's grounding zone make it difficult to assess the role of intrinsic glacier dynamics, or more complex ice-sheet-ocean interactions, in moderating this slowdown.** Collectively, our findings underscore the importance of spatial and inter-decadal variability in **atmosphere** and ocean interactions in moderating glaciological change around Antarctica.

1 Introduction

Recent in situ and satellite remote sensing campaigns have played an important role in constraining the relative roles of ice, ocean and **atmosphere** interactions responsible for controlling the substantial ice losses observed in the Amundsen Sea Sector of West Antarctica over the last ~25 years (Rignot et al., 2008; Mouginot et al., 2014**; Sutterley et al., 2014**). Comprehending the drivers of these ice losses is imperative for **accurately projecting the contribution of the West Antarctic Ice Sheet to global sea level rise** in the coming decades (e.g., Vaughan et al., 2013). Observations of the ice streams and glaciers draining into this sector, in particular Pine Island and Thwaites Glaciers, have revealed rapid grounding-line retreat (cf. Park et al., 2013; Rignot et al. 2014; Scheuchl et al., 2016), pronounced ice-dynamic thinning (Pritchard et al., 2009; 2012; Konrad et al., 2017), ice-flow-speedup (Mouginot et al., 2014; Gardner et al., 2018), and large ice-shelf melting rates (Depoorter et al., 2013; Rignot et al., 2013; **Paolo et al., 2015;** Gourmelen et al., 2017**a**). These phenomena have been attributed to oceanic and **atmospheric** forcing impinging on the West Antarctic margin (e.g., Jacobs et al., 2011; Dutrieux et al., 2014; Webber et al., 2017).

Whilst the processes driving ice-ocean-**atmosphere** interactions are being increasingly elucidated for the Amundsen Sea Sector (Jenkins et al., 2016; Asay-Davis et al., 2017; Turner et al., 2017), they remain poorly constrained elsewhere along coastal West Antarctica owing to a dearth of glaciological, oceanographical and climatological observations. Some recent studies have highlighted accelerated dynamic thinning along the Bellingshausen Sea margin (Helm et al., 2014; Paolo et al., 2015; Wouters et al., 2015; Christie et al., 2016; Gardner et al., 2018) potentially linked to **atmosphere-ocean** forcing similar to that at work in the Amundsen Sea Sector (e.g. Holland et al., 2010; Zhang et al., 2016). Along the Marie Byrd Land coastline of West Antarctica between Thwaites Glacier and the Ross Ice Shelf, little published research exists on the pace and variability of glaciological change or its drivers. Nonetheless, parts of this region have also exhibited rapid downwasting and probable dynamic imbalance over at least the last two decades (e.g., Pritchard et al., 2012; Shepherd et al., 2012; McMillan et al., 2014), notably along the ~650 km-wide Getz Ice Shelf, which has been identified as one of the largest contributors of meltwater originating from sub-ice-shelf melting in Antarctica (Depoorter et al., 2013; Jacobs et al., 2013; Rignot et al., 2013).

In this paper, we present changes in the position of the grounding line along the Marie Byrd Land coastline of West Antarctica, as identified from medium-resolution optical satellite imagery (Landsat and ASTER) between 2003 and 2015. We also recover contemporaneous ice-thinning rates from ICESat laser-altimetry and CryoSat-2 radar-altimetry records. We compare these glaciological observations with ERA-Interim climate reanalysis records of the offshore wind field, which acts as a proxy for the intrusion of warm circumpolar deep water (hereafter CDW) onto the continental shelf.

2 Methodology

We define our study domain as the coastline of West Antarctica from parallels 114° W to 157° W (Fig. 1). We term this region, which encompasses the western periphery of Getz Ice Shelf to the eastward limit of the Ross Ice Shelf front, the Marie Byrd Land Sector (hereafter MBLS).

2.1 Grounding-line detection and change quantification

To track changes in the position of the MBLS grounding line (hereafter GL), we follow the methodology detailed in Christie et al. (2016). For background, we briefly lay out the main principles of this technique.

We use medium-resolution optical satellite imagery to delineate the break-in-slope across the grounding zone, otherwise known as the "inflexion point", I_b, defined as the most seaward continuous surface-slope break detectable in optical satellite imagery (Scambos et al., 2007; Fricker et al., 2009). Used as a proxy for the true GL, which cannot be recovered directly from satellite remote sensing, I_b appears as a clearly-defined shadow-like change in on-screen pixel intensity (cf. Bindschadler et al., 2011). Most commonly situated approximately 1-2 km downstream of the true GL, I_b typically represents the structural transition from undulating, subglacial-terrain-modulated grounded ice to smoother, floating ice where basal stresses tend towards zero seaward of the GL (see Christie et al., 2016; their Fig. S1).

We used Landsat optical imagery as our primary data source owing to its unmatched, near complete spatial-temporal coverage of the MBLS compared to other freely available remote sensing datasets capable of detecting GL position (cf., Brunt et al., 2011; Rignot et al., 2011). The data were acquired by Landsat's Enhanced Thematic Mapper (hereafter ETM+) and Operational Land Imager (hereafter OLI) sensors, on-board the Landsat 7 and 8 platforms, respectively. In addition, for selected sites during 2003, where Landsat-based mapping was precluded due to persistent cloud cover or poor data quality, we utilised geometrically corrected Terra-ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) Level 1T optical data to supplement our analyses (Fig. S1; Table S1). We tracked the position of I_b along the MBLS at approximately 50-100 m intervals for years 2003, 2008, 2010 and 2015, in order to calculate proxy-GL change over the ICESat (2003-2008) and CryoSat-2 (2010-2015) orbital campaign periods (cf. Pritchard et al., 2009; 2012; Helm et al., 2014). The majority of scenes utilised were acquired during austral summertime (January, February, March), and all scenes had a cloud coverage of <40%. For 2003 and 2008, additional Landsat scenes acquired in December 2002/2007 were utilised when 2003/2008 Landsat and ASTER spatial coverage was restricted by excessive summertime cloud cover. The final I_b products were smoothed using standard GIS tools **(cf. Depoorter et al., 2013; Christie et al., 2018)**, and reflect the mean summertime GL position for each year as resolved from all available Landsat or ASTER imagery.

There are certain conditions under which I_b from optical imagery acts as a poor proxy for the true GL. Such circumstances include the mapping of I_b over lightly grounded ice plains, where multiple or no continuous breaks-in-slope are detectable in optical imagery; instances where the location of I_b lies many kilometres landward or seaward of the true GL near ice-plains or ephemerally grounded pinning points (cf. Fricker & Padman, 2006; Fricker et al., 2009; Brunt et al., 2010; Brunt et al., 2011); and over fast-flowing ice streams, where shallow ice-surface slopes, pronounced ice-surface flowlines, and dense crevasse fields render the location of the break-in-slope ambiguous or impossible to delimit (cf. Bindschadler et al., 2011; Rignot et al., 2011). Within the MBLS, such regions include the fast-flowing Berry and De Vicq Glaciers (> 1000 m yr^{-1}; Rignot et al. (2011)), as well as a minor number of small-scale suspected ice plains and pinning points throughout the Getz and Nickerson Ice Shelves. We therefore excluded such sites, which account for <1% of the MBLS coastline, from our analysis.

Errors in delineating I_b from optical imagery are derived as a function of satellite orbital geometric error, sensor spatial resolution, and I_b pixel classification confidence, following the protocol outlined in Bindschadler et al. (2011) and Christie et al. (2016; their Text S1 and Table S2). For any given year, we estimate 1σ positional uncertainty to equal approximately ± 100 m (Landsat data) or ± 47 m (ASTER data) along the majority of the MBLS coastline (Table S1).

To propagate error between successive Landsat I_b observations, associated with combining ETM+/ETM+ (for mapped I_b years circa 2003, circa 2008) or ETM+/OLI (years 2010, 2015) sensor data, we additionally calculated the root-sum-square of the 1α-positional uncertainty values calculated for each sensor. This yielded a mean standard error of ~±140 m for most of the main coastline and surrounding islands bounded by ice shelves (Table S2). To calculate uncertainty in 2003-2008 analyses, where 2003 ASTER L1T imagery was utilised in lieu of missing Landsat spatial coverage, the same calculation was applied. Whilst the propagated uncertainty associated with combining ASTER L1T and Landsat ETM+ data (±113m; Table S2) is less than that calculated for combined ETM+/ETM+ and ETM+/OLI sensor observations, for ease of comparability between multi-sensor analyses (Figs. 1 and 2), error values were upscaled to match Landsat-based estimates (~±140 m).

For most of the coastline, any overall imprecision in locating I_b (on the order of ~10-100 m) is outweighed by changes in its position over 5 years, i.e. GL advance or retreat on the order of ≥ 10^2-10^3 m. These uncertainties broadly match the positional errors reported in other satellite-based GL detection studies (cf. Brunt et al., 2010; 2011; Rignot et al., 2011; Joughin et al., 2016; Scheuchl et al., 2016). Additional confounding variables such as diurnal tidal variability and atmospheric forcing - previously recognized as important controls on GL migration over much shorter temporal baselines (Anandakrishnan et al., 2003; Fricker et al., 2009; Brunt et al., 2010) - are assumed to be negligible over the timescales we consider (cf. Milillo et al., 2017).

Upon completion of mapping, GL advance and retreat magnitudes were derived using the procedure detailed in Christie et al. (2016; their Sect. 2.3 and Text S2). Here, we defined our mapped 2015 I_b line as a baseline. This baseline was partitioned into 30 km segments along the length of the MBLS coast, which permitted the derivation of normal polylines extending infinitely landward and seaward along the outer limits of each segment, intersecting the mapped I_b lines recovered for earlier years. This enabled the creation of GL change polygons representing I_b migration (advance, retreat) over ($2015_{baseline} - y$), where y = earlier mapped year of interest, and permitted the calculation of I_b advance/retreat rates between 2003-2008 and 2010-2015 (Data Set S2).

2.2 Surface elevation and floating ice thickness changes

We compared GL migration along the MBLS with contemporaneous surface elevation change rates derived from ICESat laser- (2003-2008) and CryoSat-2 radar-altimetry records (2010-2016). We used the data of Pritchard et al. (2009; 2012) to ascertain ICESat era surface elevation change rates (Δh/Δt) over grounded and floating ice within our domain. Following Pritchard et al. (2009; their Text S1) and Pritchard et al. (2012; their Text S1.1), these datasets were derived from the interpolation of successive near-repeat track median-filtered data acquired over the MBLS, and were converted into smoothed, 10 km grids of mean Δh/Δt calculated over a 30 km radius. Grids of Δh/Δt over grounded and floating ice were processed independently to avoid averaging over the grounding zone, and data acquired over other areas suspected to be not freely-floating were culled prior to the gridding. Following Pritchard et al. (2012; their Text S1.4 and Table S1), we estimate mean absolute uncertainty in ICESat area-averaged Δh/Δt to be ~ ± 0.04 m yr^{-1} and ± 0.08 m yr^{-1} over floating and grounded ice, respectively. Over floating ice, Δh/Δt was subsequently converted into ice-shelf-thickness change rates (ΔT/Δt) following a similar methodology to Pritchard et al. (2012), using an assumed ice density of 917 kg m^{-3} (cf. Shepherd et al., 2010; Paolo et al., 2015). Propagated uncertainties associated with this conversion equal ± 0.40 m yr^{-1}.

To obtain surface elevation changes over the CryoSat-2 era, we applied a novel, recently documented swath processing technique (Foresta et al., 2016; Gourmelen et al., 2017**a**) to CryoSat-2 Synthetic Aperture Radar Interferometric (hereafter SARIn) mode data acquired between 2010 and 2016 over the MBLS. Previously applied to other regions of Antarctica (Christie et al., 2016; Smith et al., 2017; Gourmelen et al., 2017**a**), this technique offers one to two orders of magnitude more elevation measurements than conventional point-of-closest-approach (hereafter POCA) altimetry techniques, thereby maximising spatial coverage and spatial-temporal resolution of ice-sheet marginal areas, including over floating ice (Gourmelen et al., 2017**a**). Numerous corrections were implemented to the L1b dataset during the production of the swath dataset, including, over floating ice, the negation of ocean loading/tidal effects using the CATS2008A tidal model (Padman et al., 2002; following Pritchard et al., 2012); Gourmelen et al. (2017**a**) provide a comprehensive discussion of these processes.

We derived linear rates of surface elevation change from time-dependent swath elevation data acquired between 2010 and 2016 using a plane fit approach on a 10 km grid posting (cf. Gourmelen et al., 2017b). This posting was chosen to match the spatial resolution of our gridded ICESat Δh/Δt dataset, in order to facilitate comparison of changes in Δh/Δt between the ICESat and CryoSat-2 eras. Over floating ice, we additionally employed a Lagrangian framework to derive elevation and rates of surface elevation change to avoid interference associated with the advection of ice-shelf topography through time (Dutrieux et al., 2013; Moholdt et al., 2014; Gourmelen et al., 2017**a**). To do this, we used the MEaSUREs (Making Earth System Data Records for Use in Research Environments) version 2 dataset (Rignot et al., 2017) and additional ice velocity fields generated from feature-tracking of Landsat 8 imagery for the period 2013-2016 (Dehecq et al., 2015) to calculate and assign the position that each CryoSat-2 swath measurement would have had at the beginning of the CryoSat-2 operational period (July 2010). Finally, we corrected for the effects of surface mass balance and firn compaction processes throughout MBLS using the RACMO2.3p2 (5.5 km) and IMAU-FDM (5.5 km) models (Ligtenberg et al., 2011; Lenaerts et al., 2012; Van Wessem et al., 2014; Van Wessem et al., 2016; Gourmelen et al., 2017**a**; Lenaerts et al., 2017). Final uncertainties associated with the swath processing technique were recovered following Gourmelen et al. (2017**a**; their Text S1), and average ± 0.03 m yr^{-1} over both grounded and floating ice.

Over floating ice, CryoSat-2 era surface elevation change rates were transformed into thickness change rates using the same methodology as for ICESat data, with a propagated uncertainty of ± 0.30 m yr^{-1}. Three-monthly shelf-averaged thickness change rates were also obtained as part of the swath processing technique, using the methodology of Foresta et al. (2016), prior to the Lagrangian correction detailed above. This permitted the comparison of mean shelf-ice thickness changes against the 2003-2008 (ICESat era) and longer-term radar-altimetry-derived record (Paolo et al. (2015), see also Sect. 3).

2.3 Ice-atmosphere-ocean proxies

To investigate the role of **atmospheric and** oceanic forcing on glaciological change between 2003 and 2015, we examined mean zonal wind and Ekman vertical velocity anomalies on and near the MBLS' continental shelf, using ECMWF ERA-Interim climate reanalysis data (cf. Dee et al., 2011). **These methods were utilised due to a dearth of spatially and temporally continuous in-situ oceanographical observations within the MBLS during the observational period, with the last comprehensive and publically-available surveys having been carried out in 2000 and 2007 (Jacobs et al., 2013).**

2.3.1 Zonal wind anomalies

Previously established to be a reliable proxy for warm circumpolar deep water upwelling and intrusion onto West Antarctica's continental shelf (Thoma et al., 2008; Steig et al., 2012; Dutrieux et al., 2014), 10 m zonal wind anomalies (hereafter *U*) along the MBLS continental-shelf slope and break (hereafter CSB) were calculated using ERA-Interim monthly mean of daily mean model outputs (Dee et al., 2011), for all months between January 1979 and December 2016 inclusive. Anomalies were derived by subtracting long-term monthly mean values from the monthly mean of daily mean dataset, beginning in January 1979. To examine inter-decadal variability in *U*, monthly anomalies were averaged over annual timescales to simplify comparison between successive years (see Sect. 3.3).

2.3.2 Ekman vertical velocity

A derivative of the wind stress field, Ekman vertical velocity, approximates the rate at which the wind stress curl raises subsurface isopycnals, and can be used as a **first-order estimate** for Ekman transport-induced upwelling of interior ocean water masses, including relatively warm upper CDW layers (Marshall & Plumb, 2008). Ekman vertical velocities (hereafter *wE*) were calculated by converting 10 m zonal and meridional wind anomalies into relative wind stresses in fixed grid x (zonal) and y (meridional) planes (τ_x and τ_y, respectively; Nm s^{-1}), using the quadratic stress law detailed in Marshall & Plumb (2008, their Equation 10-1) with an assumed ocean-air neutral drag coefficient of 1.5 x 10^{-3} (dimensionless; cf. MacGregor et al., 2012; Smith et al., 1988). *wE* was then obtained from:

$$wE = \nabla\times((\tau_x, \tau_y) \cdot \frac{1}{p_w f}) \quad \text{(cf. Marshall \& Plumb, 2008; their Equation 10-8)} \qquad (3)$$

$$f = 2\omega Sin(\varphi) \qquad (4)$$

where f denotes the Coriolis parameter at latitude φ; ω is the Earth's angular velocity (7.292 × 10^{-5} rad s^{-1}); and p_w is the density of the Ekman layer ocean water (1027.5 kg m^{-3}). *wE* anomalies were derived from the mean of all ERA-Interim grid cells located on the continental shelf, shelf break and slope of the MBLS. As for zonal wind calculations (Sect. 2.3.1), monthly anomalies were annually-averaged to examine inter-decadal variability in *wE* (see Sect. 3.3).

[Fig. 1 here]

3 Results

3.1 Grounding-line change 2003-2015

Figure 1 indicates that from 2003 to 2015 GL retreat occurred along ~33% of the MBLS coastline. This quantity incorporates the entire mainland coastline and Siple and Carney Islands. No net GL advance was observed from 2003 to 2015. The greatest retreat occurred along Getz Ice Shelf, particularly across its central sector between Wright and Dean Islands ('Central' region in Fig. 1, inset), and near the western edge of Getz Ice Shelf, adjacent to De Vicq and Berry Glaciers ('West', Fig. 1 inset). The greatest magnitude of GL retreat totalled 1.72 ± 0.14 km on Scott Peninsula (corresponding to Segment 9 in Data Set S2). Locally-averaged GL retreat was ~0.60 ± 0.14 km along both the central sector (segments 9-24) and the western edge of the ice shelf (segments 27-31).

In contrast to Getz Ice Shelf, the GL west of 135° W – which fringes Hull and Land Glaciers and the ice streams draining into Nickerson Ice Shelf – underwent more limited or negligible migration between 2003 and 2015, with maximum retreat occurring across Land Glacier (0.54 ± 0.14 km; Segment 45 in Data Set S2). Farther west, with the exception of minor retreat near Scambos Glacier (0.22 ± 0.14 km; Segment 83 in Data Set S2), no GL migration took place along the entire perimeter of Sulzberger Ice Shelf, nor throughout the neighbouring Swinbourne Ice Shelf or Bartlett Inlet regions (Fig. 1).

Collectively, our observations highlight the tendency for GL retreat to be clustered around areas of deeply bedded ice (Fig. 1), which correspond to regions of recent moderate-to-fast ice flow inland of the GL (>500 m yr^{-1}; cf. Rignot et al. (2011)). Furthermore, partitioning our GL observations into change over the ICESat versus CryoSat-2 campaign periods, we detect several notable patterns of GL migration with respect to ice-sheet altimetry observations. These findings are discussed next.

3.2 Glaciological change 2003-2008 (ICESat era)

Between 2003 and 2008, GL retreat along Getz Ice Shelf emulated the spatial pattern observed over the longer timeframe of 2003-2015 (Fig. 1, Fig. 2a). The Getz Ice Shelf over the ICESat era also hosted the largest GL retreat rates observed over the observational period (Fig. 2). Retreat rates along the central and western sectors of Getz Ice Shelf ranged from 34 ± 30 m yr^{-1} (Segment 16; Dataset S2) to 319 ± 30 m yr^{-1} and 192 ± 30 m yr^{-1} on Scott Peninsula and near Berry Glacier, respectively (Segments 9, 30). Over the same period, no GL migration occurred across the eastern sector of Getz Ice Shelf ('East', inset of Figs. 1 and 2).

The GL retreat observed along the central-western Getz Ice Shelf was also associated with ice surface lowering of up to 120 km inland of the 2008 grounding zone (Fig. 2a). Simultaneously, the ice shelf thinned at an average of 1.76 ± 0.40 m yr^{-1} (Fig. 3a), where maximum thinning of 3.8 ± 0.40 m yr^{-1} was focussed across the central sector between Scott Peninsula and Carney Island (Fig. 3b), i.e. encompassing the locations at which some of the largest GL retreat rates had occurred. Nevertheless, not all instances of GL retreat over the ICESat era were associated with the locations of highest thinning along Getz Ice Shelf; for example, GL retreat of up to 110 ± 30 m yr^{-1} occurred near Dean Island ('D' on Fig. 3(b); Segments 21-23; Data Set S2) where ice-shelf thinning was relatively more limited in magnitude (~1-1.8 ± 0.40 m yr^{-1}).

West of 135°, almost no GL retreat was observed over the ICESat era outwith Landsat/ASTER 1σ-error bounds (Fig. 2a). In conjunction, ice-surface lowering was less pronounced than along Getz Ice Shelf (Fig. 2a), with negligible overall change in corresponding ice-shelf thinning rates across Nickerson, Sulzberger and Swinbourne Ice Shelves (not shown).

[Fig. 2 here]

3.3 Glaciological change 2010-2015 (CryoSat-2 era)

During 2010-2015, GL retreat continued to occur along Getz Ice Shelf but on average 68% slower than in 2003-2008 (Fig. 2b). This reduction in GL retreat was evident even in the central sector of Getz Ice Shelf, where we detect the most rapid GL retreat during this timeframe (Fig. 2b; max. 98 ± 30 m yr^{-1}; Segment 19, Dataset S2). In addition, a minor segment of the central Getz Ice Shelf GL underwent limited advance (33 ± 30 m yr^{-1}; Segment 15, Dataset S2), in conjunction with more minor or negligible GL retreat across both Scott Peninsula and throughout the western sector of the ice shelf (Fig. 2b).

Inland, the ice surface continued to lower (Fig. 2b) as it had done over the previous (ICESat) era (Fig. 2a), with the greatest lowering of grounded ice having occurred upstream of the central and western sectors of the ice shelf. The most notable contrast in $\Delta h/\Delta t$ between the two eras was an enhanced thinning signal up to ~50 km inland of the 2015 GL along the central Getz Ice Shelf between Scott Peninsula and Siple Island, and at and near De Vicq and Berry Glaciers, where thinning rates intensified and propagated up to 82 km inland (Fig. 2b; Fig. S2). Over the same period, with the exception of a slowdown in cumulative thickness change between 2011 and 2013, Getz Ice Shelf thinned at an average rate of 1.51 ± 0.30 m yr^{-1}, not significantly different to the rate over the ICESat era (1.76 ± 0.40 m yr^{-1}), nor the longer-term (1994-2012) radar altimetry-based record (~1.60 ± 0.30 m yr^{-1}; Fig. 3a; Paolo et al. (2015, their Table S2)). At the local scale, along a large proportion of the central Getz Ice Shelf and west of Dean Island (western Getz Ice Shelf), there was a localised slowdown in ice-shelf thinning (≥ 4.00 ± 0.30 m yr^{-1}) corresponding to the observed locations of slowdown in GL retreat rate (Fig. 3b and c; Fig. S3). A few locations experienced a localised increase in ice-shelf thinning, e.g. west of Berry Glacier, where we observe a reduction in GL retreat, and downstream of De Vicq Glacier, where no GL change information could be recovered from our optical mapping technique (cf. Sect. 2.1.1).

Across the remainder of the MBLS, including the eastern Getz Ice Shelf and the region west of 135° W, we detect negligible GL change between 2010 and 2015, apart from localised retreat at Land Glacier (86 ± 30 m yr^{-1}; Fig. 2b; Segment 45 in Dataset S2). With the exception of Hull and Land Glaciers and near Swinbourne Ice Shelf, where surface elevation change rates increased inland of the GL (Fig. 2a and b, Fig. S2), these areas exhibited no significant change in the pace of ice surface lowering (Fig. 2b; Fig. S2) or ice-shelf thinning (not shown) relative to the earlier ICESat era.

[Fig. 3 here]

3.4 Ice-atmosphere-ocean interactions: Zonal wind and Ekman vertical velocity

Figure 4 displays annually-averaged 10 m zonal wind (U) and Ekman vertical velocity (wE) anomalies offshore of the MBLS (114° W to 157° W). We detect a significant positive (westerly) anomaly in U along the CSB of the MBLS during most of the ICESat era (2003 to 2008, inclusive; Fig. 4a), the peak magnitude of which was unprecedented within the ERA-Interim data record (max. MBLS U = 1.15 m s^{-1}; 2005). This phenomenon is echoed in the wE record (Fig. 4b), which reveals a predominant net upwelling during this epoch (max. wE = 2.94 myr^{-1}; 2006). As for U, this wE anomaly was also exceptional in the ERA-Interim record, although similar peaks were subsequently recorded in 2009 and 2015. Conversely, for most of the CryoSat-2 era (2010 to 2013, inclusive), *U* was predominantly negative (easterly), with averaged zonal wind reaching record negative values during 2012 (min. $U = -1.30$ m s^{-1}). This wind anomaly was associated with an overall marked reduction in the tendency for upwelling to occur across MBLS from circa. 2008/2009, with minimum upwelling ($wE = -3.34$ m yr^{-1}) rates also recorded in 2012. Following 2013, *U* tended back towards zero, becoming positive (westerly) from 2014 onwards, and this was responsible for the significant upwelling event observed in 2015 (max. $wE = 3.21$ m yr^{-1}).

Differences in the spatial distribution of *wE* for January 2010 to December 2013 (inclusive) minus January 2003 to January 2008 (inclusive) relative to the long-term ERA-Interim record are plotted in Fig. 5**c**. Comprising of persistently easterly *U* anomalies prior to 2014 (Fig. 4a), this epoch was characterised by a much reduced *wE* throughout the MBLS relative to 2003-2008 (Fig. **5a, b**). Predominantly centred at ~140-145° W, which ranges spatially between Sulzberger Ice Shelf and the western edge of Getz Ice Shelf, additional, strongly negative Ekman vertical velocities were also present along the eastern edge and much of the central Getz Ice Shelf during this epoch **(Fig. 5c)**. Over the same period, a notable reduction in *wE* near ~115° W, 70° S also occurred.

In summary, the ERA-Interim observational record shows the predominance of Ekman upwelling during the ICESat era (2003-2008), forced by the strongest westerly wind anomaly in the record, followed by a tendency for reduced Ekman upwelling associated with an easterly wind anomaly during most of the CryoSat-2 era (2010-2015).

[Fig. 4 here]

[Fig. 5 here]

4 Discussion

Our observations have highlighted that over a 12-year period there has been considerable spatial and temporal variability in the nature and pace of GL migration throughout the MBLS (Figs. 1 and 2). In the following sections, we examine the potential drivers of these phenomena, with respect to regionally contrasting ice, ocean, **atmosphere** and other potential interactions at work across the MBLS. To support our discussion we make reference to a conceptual model presented in Fig. 6.

[Fig. 6 here]

4.1 Getz Ice Shelf grounding-line change 2003-2015

The most prominent GL retreat throughout the MBLS occurred along the ~650 km Getz Ice Shelf (Fig. 1; Sect. 3.1), which neighbours the recent, rapidly downwasting ice-masses of the wider Amundsen Sea Sector. This was a likely consequence of the substantial thinning and basal melting witnessed over this region in recent decades**, indicative of an on-going dynamically-driven glaciological imbalance through time** (Figs. 2 and 3; see also Pritchard et al., 2009; 2012; Jacobs et al., 2013; Paolo et al., 2015). **Indeed, a**ll GL retreat within the central and western sectors of Getz Ice Shelf occurred directly upstream of well-surveyed, deep (>400 m) bathymetric depressions north of the ice fronts (Fig. 1), which transect the continental shelf and route warm modified-CDW from the CSB to the sub-ice shelf cavity (Wåhlin et al., 2010; Arneborg et al., 2012; Jacobs et al., 2013; see also our Fig. 6a). Aping the offshore geological setting of the Bellingshausen and eastern Amundsen Sea Sectors, where recent glaciological change is believed to have been facilitated by CDW ingress along similar cross-continental-shelf conduits (Nitsche et al., 2007; Walker et al., 2007; Bingham et al., 2012; Pritchard et al., 2012; St-Laurent et al., 2013; Zhang et al., 2016), these observations are strongly suggestive of ocean-forced glaciological change at work across the central-western Getz Ice Shelf and its inland basins between at least 2003 and 2015.

Along the eastern sector of the ice shelf, where we detect almost no GL migration between 2003 and 2015 (See Sect 3.1. and 3.2.; Fig. 1), ice-flow velocities (Rignot et al., 2011; Gardner et al., 2018) and ice-thinning rates (Figs. 2 and 3) were more limited relative to the remainder of the ice shelf. This is despite the proximity of the deep Getz-Dotson Trough to the eastern sector's ice front (Fig. 1). Collectively, these observations imply that local-scale ice-ocean processes or geological configurations underneath the most easterly portion of Getz Ice Shelf may render the region relatively immune to ocean-forced dynamic thinning and subsequent GL retreat. **These considerations are discussed in further detail next (Section 4.2).**

4.2 Controls on Getz Ice Shelf grounding-line dynamics

4.2.1 Atmosphere-ocean forcing

That GL retreat slowed down consistently along the length of the (~650 km long) central-western Getz Ice Shelf in the CryoSat-2 era relative to the ICESat era (Fig. 2; Fig. S3; Sect. 3.3) is indicative of regional-scale external forcing, primarily with respect to the intensity of **atmosphere-ocean** forcing of Getz Ice Shelf through time. Indeed, the changes in 10 m zonal wind, *U* (Fig. 4a), and Ekman vertical velocity, *wE* (Fig. 4b), suggest that the 2010-2015 era was characterised by a predominantly easterly wind anomaly over the MBLS CSB (Sect. 3.4), in conjunction with an implied regional-scale reduction in CDW upwelling and flooding onto the continental shelf. These findings are fully synchronous with similar **ocean-atmosphere** trends observed over the wider Amundsen Sea Sector since 2009 (Dutrieux et al., 2014), which were responsible for a much deepened CDW layer across this region of West Antarctica relative to the ICESat era (cf. Wåhlin et al., 2010; Jacobs et al., 2013; Dutrieux et al., 2014; Webber et al., 2017). Dutrieux et al. (2014; following Steig et al., 2012) attributed this behaviour to inter-decadal variability in tropical-pacific ENSO forcing and so, by extension, Getz Ice Shelf and the wider MBLS also appear responsive to inter-decadal variability in global-scale **atmospheric** forcing. **This hypothesis concurs with the recent findings of Paolo et al. (2018) who examined the response of ENSO variability on all pacific-facing ice shelves over the radar altimetry record (1994-2017), as well as the earlier findings of Jacobs et al. (2013), who attributed a reduced thermocline and glaciological forcing along Getz Ice Shelf in the years preceding the ICESat era to a strong La Niña event circa. 2000.**

Locally, the significant negative difference in *wE* near the eastern Getz Ice Shelf is also notable (Fig. 5**c**). Widespread along the eastern and parts of the central Getz coast between 2010 and 2014, this anomaly was prevalent across the deeply-bedded coastal tributaries of the Getz-Dotson Trough (Fig. 1), which act as the primary CDW ingress pathways to the eastern and central sectors of the Getz Ice Shelf (Wåhlin et al., 2010; Arneborg et al., 2012; Jacobs et al., 2013). Likely related to changes in the spatial extent of the Amundsen Sea Polynya since 2003-2008 (cf. Nihashi & Ohshima, 2015; 2017; Kim et al., 2017), we hypothesise that the net reduced upwelling inferred to have occurred at this coastal location, consistent with a much deepened isopycnal depth over the trough's tributaries, may have been responsible for an additional, locally-forced reduction in central and eastern Getz-bound CDW inflow during 2010-2015. Such a reduction – together with observations of deeply reduced *wE* along much of the remaining Getz Ice Shelf and wider MBLS between 2010 and 2014 (Fig. 5**c**)- may explain the overall, central-western Getz-wide reduction in GL retreat relative to the 2003-2008 (ICESat) era, and may have simultaneously bolstered the eastern ice shelf's overall immunity to pervasive ocean-forced GL retreat (Figs. 1 and 2). Similar local-scale processes are believed to have governed the magnitude of change at Pine Island Glacier in recent years, where a dramatic reduction in basal melt rate and other glaciological change was observed between 2011 and 2013 (Dutrieux et al., 2014; Mouginot et al., 2014; St. Laurent et al., 2016; Webber et al., 2017). Over the same timeframe, where we detect minimum *U* and *wE* across the MBLS (Figs. 4a and b; Sect. 3.4), such processes may also have induced the temporary hiatus in shelf-averaged thickness change witnessed between 2011 and 2013, where mean Getz Ice Shelf thinning rates appear to have abated contrary to the longer-term CryoSat-2 trend (Fig. 3a; also Sect. 3.3).

Our findings underscore the **potential** importance of inter-decadal variability in both regional- and local-scale **atmosphere** and ocean interactions in moderating glaciological change along this sector of Antarctica (Fig. 6). **Our observations also highlight the need for continuous in-situ ocean observations near and underneath Getz Ice Shelf in the future. Such observations would yield greater insight into the specific oceanographic mechanisms controlling the hydrography of Getz Ice Shelf's sub-shelf cavity (cf. Jacobs et al., 2013; Kim et al, 2017; Webber et al., 2017), beyond the approximations presented here and the spatially and temporally-limited observations previously reported (e.g. Wåhlin et al., 2010; Jacobs et al., 2013).** However, whilst an apparent correlation exists between Getz Ice Shelf GL retreat rate and inter-decadal variability in **atmosphere-ocean** forcing (cf. Sect. 3.4 and 4.2.1), observations of generally unabated CryoSat-2 shelf-averaged thinning rates relative to earlier records (Fig. 3a; Pritchard et al. (2012); Paolo et al. (2015)) suggest that additional processes may have facilitated the observed slowdown in 2010-2015 GL retreat along parts of ice shelf. That is, such temporally sustained ice-shelf thinning (Fig. 3a) would be expected to augment progressive GL retreat over time (cf. Schoof, 2007), contrary to the observed GL-retreat slowdown. Possible confounding factors are surface mass balance processes, grounding zone bed geometry, and local-scale changes in ice dynamics.

4.2.2 Surface mass balance processes

Temporal changes in surface mass balance must be accounted for in order to resolve the relative influence of surface- and/or dynamically-induced (i.e. ocean-forced) processes controlling surface elevation change (see Pritchard et al., 2012; Helm et al., 2014; Wouters et al., 2015 for further discussion). For example, marked inter-annual variability in surface accumulation was believed to have played a leading role in driving the enhanced surface lowering witnessed over the Southern Antarctic Peninsula in recent years (cf. Helm et al., 2014; following Thomas et al., 2008).

Near Getz Ice Shelf, where several studies have highlighted trends of increased ice mass loss in recent years (e.g., McMillan et al., 2014; Gardner et al., 2018), negative trends in surface mass balance have recently been documented inland of the GL (up to 0.80 m yr^{-1} between 2006 and 2015; Chuter et al. (2017); see also their Fig. S4). However, whilst negative surface mass balance is believed to have controlled a large proportion of ice loss over grounded ice in the MBLS (Chuter et al., 2017), we note that that such decreases are insufficient to explain the pronounced ice-shelf thinning and basal melting rates observed seaward of the GL over the ICESat (Fig. 3a; Depoorter et al., 2013; Jacobs et al., 2013) and CryoSat-2 (Sect. 3.3 and Fig. 3a) eras. Moreover, recent modelled estimates over Getz Ice Shelf reveal only minor temporal changes in surface mass balance trend (Lenaerts et al., 2016), with 2010-2015 annual mean rates of surface mass balance (0.8 m w.e. yr^{-1}; Figure S4) not significantly different to the long term (1979-2015) average (~ 0.8-1.0 m w.e. yr^{-1}; cf. Lenaerts et al., 2017; their Figure 7). By implication, surface mass balance changes are therefore unlikely to have played a significant role in controlling the progressive thinning of Getz Ice Shelf over the CryoSat-2 era (Fig. 3a), or the observed slowdown in GL retreat rate (Figs. 2a and b; Fig. S3).

4.2.3 Grounding zone bed geometry

Bed conditions at the grounding zone of Getz Ice Shelf are poorly constrained, and are predominantly interpolated from a limited number of Operation IceBridge radar depth-sounding data and other lower-resolution geophysical datasets (Fretwell et al., 2013). Nonetheless, we note that upstream of the 2008 GL position, the inclination of surface and bed slopes along a large proportion of the Getz Ice Shelf, as inferred from Bedmap2 (Fretwell et al., 2013) and optical satellite imagery (Data Set S1), become increasingly prograde and undulating, which may act to inhibit GL retreat. That is, the potentially rough and shoaling topography upstream of the 2008 GL may require prolonged, continuously high, or increased rates of thinning to permit GL retreat – a process that has been modelled across both idealised and physically-constrained grounding zone geometries over other parts of West Antarctica (cf. Schoof et al., 2007; Durand et al., 2011; Parizek et al., 2013; Nias et al., 2016). Until more comprehensive knowledge of Getz Ice Shelf's grounding zone bed structure exists, glacier/ice-stream-specific internal variability, moderated by bed conditions at the 2010-2015 grounding zone, cannot be reliably dismissed as an additional control on the slowdown of GL retreat rate during the CryoSat-2 era. Increased geophysical survey of the entire grounding zone is therefore an important scientific objective towards more accurately assessing the future evolution of Getz Ice Shelf GL migration and glaciological (in)stability in the coming decades.

4.2.4 Changes in ice dynamics

Changes in ice dynamics, potentially correlated to differences in subglacial bed conditions (cf. Section 4.2.3), may also have played an important role in influencing GL retreat slowdown along Getz Ice Shelf during the observational period. Gardner et al. (2018) have presented changes to ice surface velocities across this region between circa. 2007/2008 and 2015. There is strong correspondence along the Getz Ice Shelf margin between the locations where we have observed GL slowdown or speedup (Fig. 2; Fig. S3) with those where Gardner et al. (2018) documented ice velocity slowdown or speedup over the same time interval. Locations of ice-velocity speedup are localised along the coastline but represent the major contributors to a recorded 6% increase in ice-mass discharge across the MBLS (Gardner et al., 2018). These locations, including the fast-flowing Berry and De Vicq Glaciers (Figs. 1 and 2), are likely outlets of thick ice (cf. Jacobs et al., 2013) characterised by a transition towards dynamically-unstable glaciological change that is now divorced from **atmosphere-ocean** forcing. Everywhere else along the central-western Getz Ice Shelf GL, the ice flow remained constant or decelerated (Gardner et al., 2018; their Fig. 8, panel 20), which is consistent with the ice-shelf-wide reduction in **atmosphere-ocean** forcing noted in Sect. 4.2.1.

4.3 Grounding-line change and its controls west of Getz Ice Shelf

Along the coastline between Getz and Ross Ice Shelves, encompassing the GL along Nickerson and Sulzberger Ice Shelves, GL migration was negligible or exhibited lower retreat than along Getz Ice Shelf between 2003 and 2015 (Fig. 1; Sect. 3.1). In addition, ice-surface lowering along the majority of this coastline was negligible over the observation window (Fig. 2).

One explanation for the muted GL response west of Getz Ice Shelf may be provided by the region's underlying geology. Along this coastline prominent mountains, likely to be of volcanic origin (Fretwell et al., 2013; Van Wyk de Vries et al., 2017), rise steeply immediately inland of the grounding zone, providing a possible regional topographic barrier to pervasive GL retreat and dynamic thinning. The few locations of notable GL retreat west of Getz Ice Shelf, for example at Land and Scambos Glaciers (Fig. 1), may be attributed to breaches of this coastal topographic barrier. These locations reside immediately upstream of deep (> 500 m), well-surveyed subglacial depressions which extend to within close proximity of the continental-shelf margin (Fig. 1; S5; Arndt et al., 2013), and which likely represent the routeways of warm-based, fast-flowing ice-streams during glacial maximum conditions (Ó Cofaigh et al., 2005; Nitsche et al., 2016).

Another inhibitor of GL change west of 135° W may derive from regional contrasts in the structure of the continental shelf seaward of Getz Ice Shelf versus farther west. In neighbouring regions of West Antarctica, continental shelves fronted by shallower shelf slopes and bisected by multiple troughs are critical for permitting sustained upwelling, ingress and shoreward transportation of CDW towards the GL (e.g., Bellingshausen Sea Sector (Ó Cofaigh et al., 2005; Bingham et al., 2012), Amundsen Sea Sector including Getz-Dotson Trough (Walker et al., 2007; Wåhlin et al. 2010)). By contrast, the continental shelf west of 135° W is characterised by a shallower seafloor fronted by a steeper continental shelf slope, and the general absence of significant, shelf-bisecting troughs that breach the CSB (Fig. 1; Fig. S5). Indeed, from in-situ measurements Jacobs et al. (2013) recovered only intermittent CDW presence along the length of the CSB west of 135° W, while Schmidtko et al. (2014) showed that rates of long-term CDW shoaling across the same region were more restricted compared with the Amundsen and Bellingshausen Sea Sectors. Recent work utilising an ocean eddy-resolving model, parameterised to account for the effects of variable continental-shelf geometry on CDW ingress, has also underscored that reduced CDW transport onto the continental shelf can be attributed to steep continental slope bathymetry in conjunction with a more pronounced Antarctic Slope Front over the CSB (Stewart & Thomson, 2015; their Fig. 2d). The Antarctic Slope Front acts to separate fresh continental-shelf surface waters from offshore CDW sources (Jacobs, 1991; Baines, 2009; Stewart & Thomson, 2015, their Figs. 1b and 2d). Together, these findings suggest that the strength of the Antarctic Slope Front may be critical to the vulnerability of the MBLS to CDW-induced GL retreat and dynamic instability (Fig. 6). Notably, Whitworth et al. (1998) traced the beginnings of a steeper Antarctic Slope Front extending westward from 120° W, while Lee & Coward (2003; cf. Thompson,

2008) independently inferred a transition to a steeper Antarctic Slope Front from modelled ocean surface current velocities at ~125-135° W. These longitudinal limits correspond broadly with the contrasting GL behaviours we have observed along and west of Getz Ice Shelf (Figs. 1 and 2).

It is important to note that the strength of the Antarctic Slope Front co-exists with, and is speculated to be influenced by, the positioning of the Antarctic Circumpolar Current (hereafter ACC) (Walker et al., 2013). The ACC drives circumpolar westerly ocean circulation and ultimately influences the upwelling and delivery of CDW from the deep ocean towards the continental shelf (Orsi et al., 1995). Across the MBLS, we note that the steepening of the Antarctic Slope Front at ~135° W strongly aligns with a marked northward deflection of the ACC from the continental-shelf slope limits at ~130-135° W. **Influenced by the position of the Ross Gyre (Assmann & Timmerman, 2005), this** ACC behaviour persists from here to the western limits of the Ross Sea at ~150° E (Fig. S6; cf. Orsi et al. (1995)), and likely partly explains the limited presence of CDW west of 135° W (cf. Jacobs et al., 2013; see also our Fig. 6b). In contrast, east of 135°W, the ACC more closely follows the shallower continental-shelf slope margins adjacent to the Getz Ice Shelf and Amundsen and Bellingshausen Sectors (Fig. S6), contributing to the previously documented presence of on-shelf CDW across these regions (Holland et al., 2010; Jacobs et al., 2013; Zhang et al., 2016) and, most likely, the observed patterns of ocean-driven GL retreat and sustained thinning throughout the Getz Ice Shelf between 2003 and 2015 (Fig. 6a).

Finally, we acknowledge that the large meltwater fluxes originating from the Amundsen Sea Sector (Jacobs et al., 2013; Rignot et al., 2013; Depoorter et al., 2013) may also play an important role in moderating ice-ocean interactions west of 135° W. A recent modelling study suggests that up to one third of the total meltwater derived from the Amundsen Sea Sector is transported towards the Ross Sea (Nakayama et al., 2014). Within this trend, up to 50% of the total meltwater content delivered to the Ross Sea originates from Getz Ice Shelf via a pronounced easterly coastal current, and Ross-Sea-bound meltwater-transportation pathways flood the entire width of the continental shelf west of 135° W (Nakayama et al., 2014; their Figs. 2b and 3c). This implies that the high volumes of meltwater originating from Getz Ice Shelf in recent years (Rignot et al., 2013), even during steady-state conditions, may be sufficient to result in the enhanced modification of on-shelf CDW across this region of the MBLS. Hypothesised to become exacerbated by future increases in dynamic basal melting of Amundsen Sea ice shelves (Nakayama et al., 2014), this process may continue to limit CDW access to the sub-shelf cavity in the coming decades, and partly explain our observations of near-negligible GL retreat and thinning rates between 2003 and 2015.

5 Conclusions

Medium-resolution optical satellite imagery shows that ~33% of the Marie Byrd Land coastline, feeding the western Amundsen Sea and eastern Ross Sea, West Antarctica, experienced grounding line retreat between 2003 and 2015. Since 2003, the grounding line has retreated pervasively along Getz Ice Shelf, but farther west has remained predominantly stable. Between 2003 and 2008 (ICESat era), the grounding line retreated more rapidly along the Getz Ice Shelf margin than between 2010 and 2015 (CryoSat-2 era), consistent with contemporaneous trends of reduced ice-shelf thinning rates through time as inferred from ICESat and CryoSat-2 altimetry data.

We find a correspondence between the observed slowdown in Getz Ice Shelf's grounding-line retreat and a reduction in external atmosphere-ocean forcing as inferred from climate reanalysis data. During the CryoSat-2 era, weaker offshore winds relative to the ICESat era reduced Ekman upwelling on and around the continental shelf, resulting in a likely decline in Circumpolar Deep Water intrusion to the sub-Getz ice-shelf cavity. This is analogous to observed changes elsewhere in the Amundsen Sea Sector since 2009 (Dutrieux et al., 2014, following Steig et al., 2012; Turner et al., 2017), and is supported by empirically-constrained trends of oceanographic change observed near Getz Ice Shelf's calving fronts in the years immediately preceding the ICESat era (Jacobs et al., 2013). However, at the local scale, grounding zone bed geometry, which is poorly constrained along much of Getz Ice Shelf, may have also played a role in modulating retreat rates. Additional near-shore ocean processes, such as eddy-mediated transport of CDW across the shelf break (Stewart & Thompson, 2015), seasonal variations in on-shelf heat transport linked to local-scale atmospheric forcing (Webber et al., 2017) and the influence of sea ice on Ekman vertical velocities (Kim et al., 2017), may also have contributed to the observed reduction in GL retreat.

We ascribe the relative glaciological stability of the Marie Byrd Land margin west of Getz Ice Shelf, encompassing Nickerson and Sulzberger Ice Shelves, to a divergence of the Antarctic Circumpolar Current from the continental-shelf break at ~130-135°W. At this longitude, the Antarctic Slope Front also intensifies in conjunction with a steepening of the continental-shelf slope and a shallowing of the continental-shelf floor. In consequence, much of the Antarctic margin between Getz and Ross Ice Shelves is buffered from the **atmosphere-ocean**-driven forcing that has been observed farther west. **Ocean modelling experiments suggest that this phenomenon may be further supplemented by on-shelf flooding of basal meltwater originating from the neighbouring Amundsen Sea Sector, including Getz Ice Shelf.**

Collectively, our findings from the Marie Byrd Land Sector underscore the importance of both spatial and inter-decadal variability in ocean and **atmosphere** interactions for moderating glaciological change around Antarctica. **To assess the importance of these interactions, increased spatial-temporal oceanographical observations and high-resolution geophysical measurements of the MBLS' geological setting are required.**

Data availability

All GL, ice frontal position and MBLS ice-mask datasets derived from this study are available at https://doi.org/10.1594/PANGAEA.884782. Landsat data used in this study are available from the USGS/NASA at earth-explorer.usgs.gov/, Cryosat-2 data are available from the European Space Agency, and ERA-Interim data are available from the European Centre for Medium-Range Weather Forecasts (ECMWF) at https://www.ecmwf.int/en/research/climate-reanalysis/era-interim. Supplementary data supporting the results of this paper are available in the accompanying supporting information file.

Author contributions

FDWC designed the study, performed all analyses, and wrote the paper under the guidance of RGB. FDWC developed the optically-derived GL detection technique and carried out GL change analysis with the assistance of RRB. NG generated the CryoSat-2 surface elevation change (Δh/Δt) data. EJS gave guidance/support to FDWC in sourcing, deriving and interpreting the ERA-Interim datasets presented in this study. HDP provided the ICESat altimetry data; and KS and SFBT added significant value to the discussion on ice-ocean-**atmosphere** interactions around West Antarctica, via several in-depth discussions with FDWC.

Competing interests

The authors declare that they have no conflict of interest.

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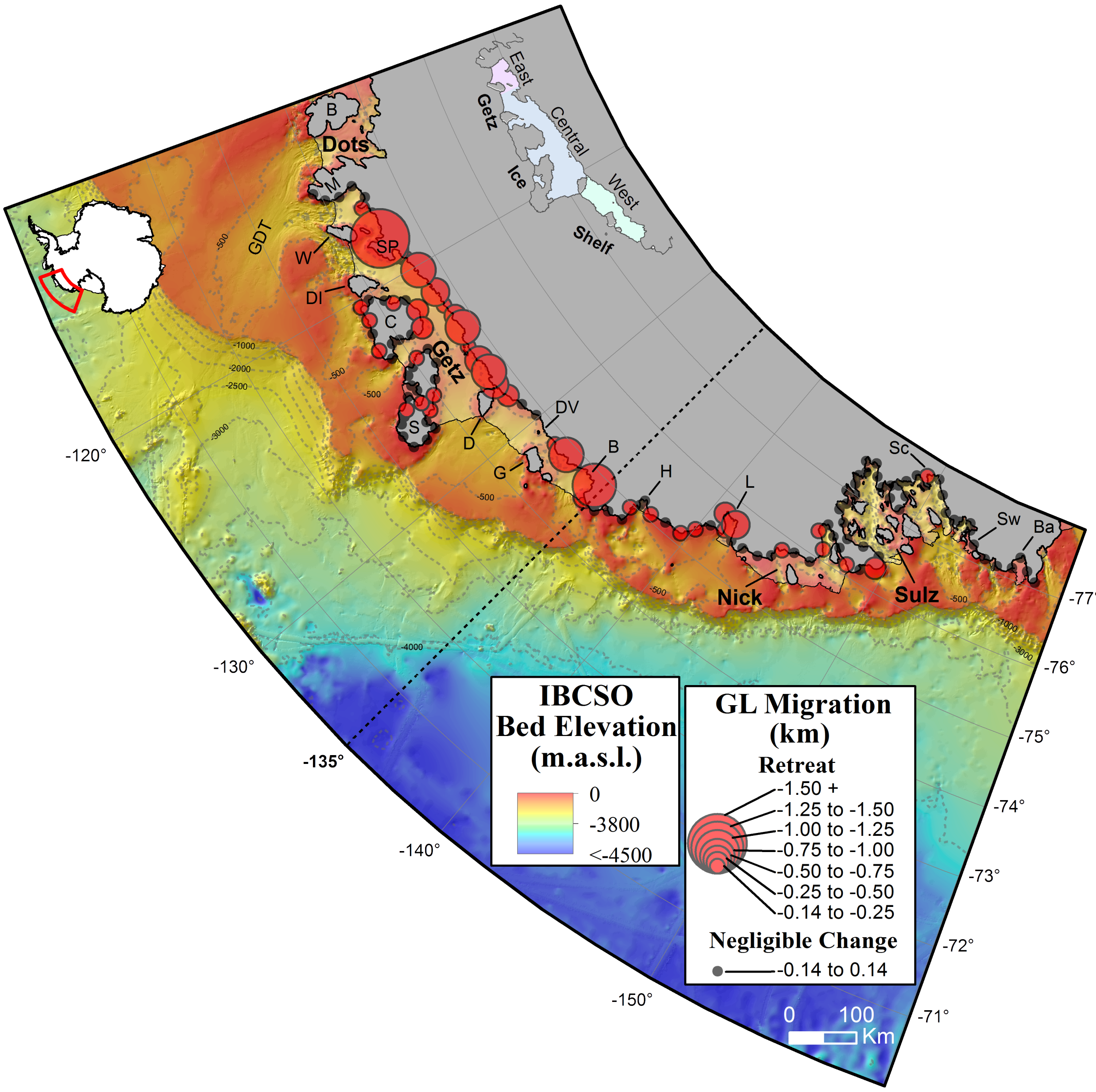

Figure 1. 2003-2015 net grounding line (GL) change along the Marie Byrd Land Sector of West Antarctica. Circle radii denote the magnitude of GL change per 30 km segment along the MBL grounding line. Small black circles denote negligible GL change detected within satellite error bounds. Note the non-linear scaling of change. Change symbols are overlaid upon MOA2009 grounded and floating ice shelf boundary masks (Haran et al., 2014); as well as IBCSO v.1 circum-Antarctic bathymetry data (Arndt et al., 2013) with 500 m (light grey) and 1000 m (dark grey) depth contours. *Dots*, *Getz*, *Nick*, *Sulz* and *Sw* denote the Dotson, Getz, Nickerson, Sulzberger and Swinbourne Ice Shelves (respectively); *GDT*, Getz-Dotson Trough; *M*, Martin Peninsula; *B*, Bear Island; *W*, Wright Island; *SP*, Scott Peninsula; *DI*, Duncan Island; *C*, Carney Island; *S*, Siple Island; *D*, Dean Island; *DV*, De Vicq Glacier; *G*, Grant Island; *B*, Berry Glacier; *H*, Hall Glacier; *L*, Land Glacier; *Sc*, Scambos Glacier and *Ba*, Bartlett Inlet (Swithinbank et al., 2003a; 2003b). Note the presence of steep continental slope break gradients situated to the west of the 135° W. North of Dotson and Getz Ice Shelves, also note the deep glacially scoured troughs that transect the continental shelf and connect present day ice fronts to the shelf break (see main text for further discussion). Inset map (top left) = location of the MBLS. Inset (top right) = eastern, central and western sectors of Getz Ice Shelf, as referred to in the main text.

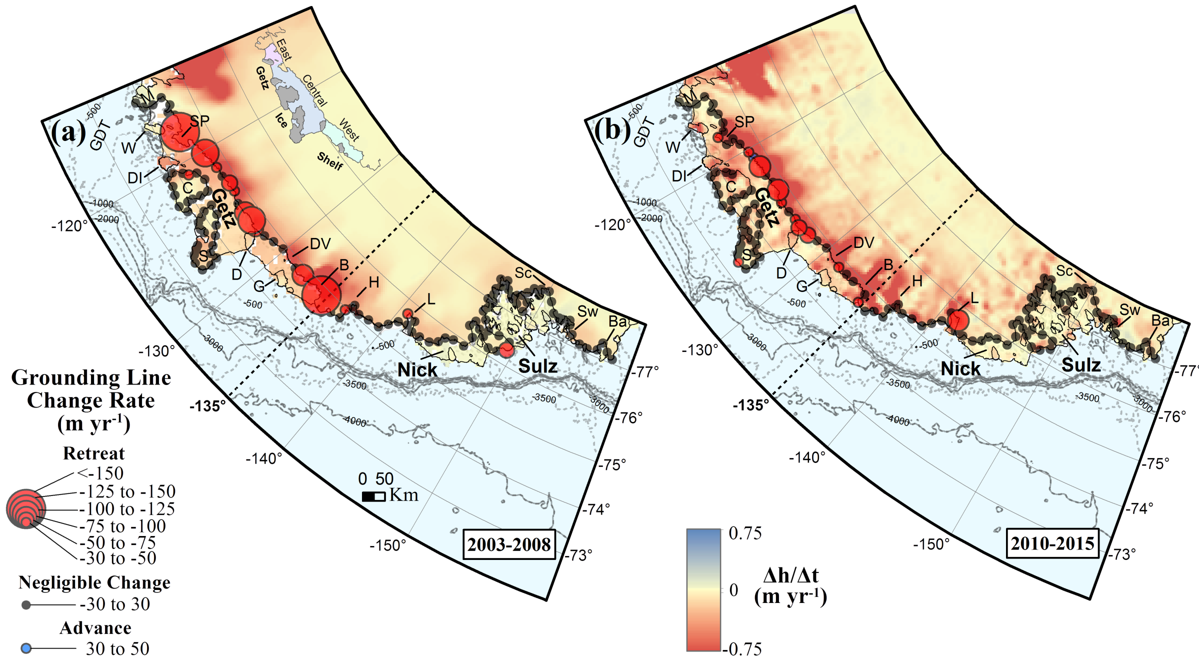

Figure 2. Rate of change in GL position throughout the Marie Byrd Land Sector over the periods (*a*) 2003-2008 and (*b*) 2010-2015. Circle radii denote the magnitude and direction of grounding line migration (red, retreat; blue, advance) per 30 km segment across the domain. As for Fig. 1, black circles denote negligible change detected within satellite error bounds. Note the non-linear scaling of change. GL migration data are superimposed over gridded surface elevation change rates (Δh/Δt; m yr^{-1}), as derived from (*a*) ICESat (Pritchard et al., 2009; 2012) and (*b*) swath processed Cryosat-2 data (this study). Bathymetric contours, site labels and Getz Ice Shelf inset same as Fig. 1.

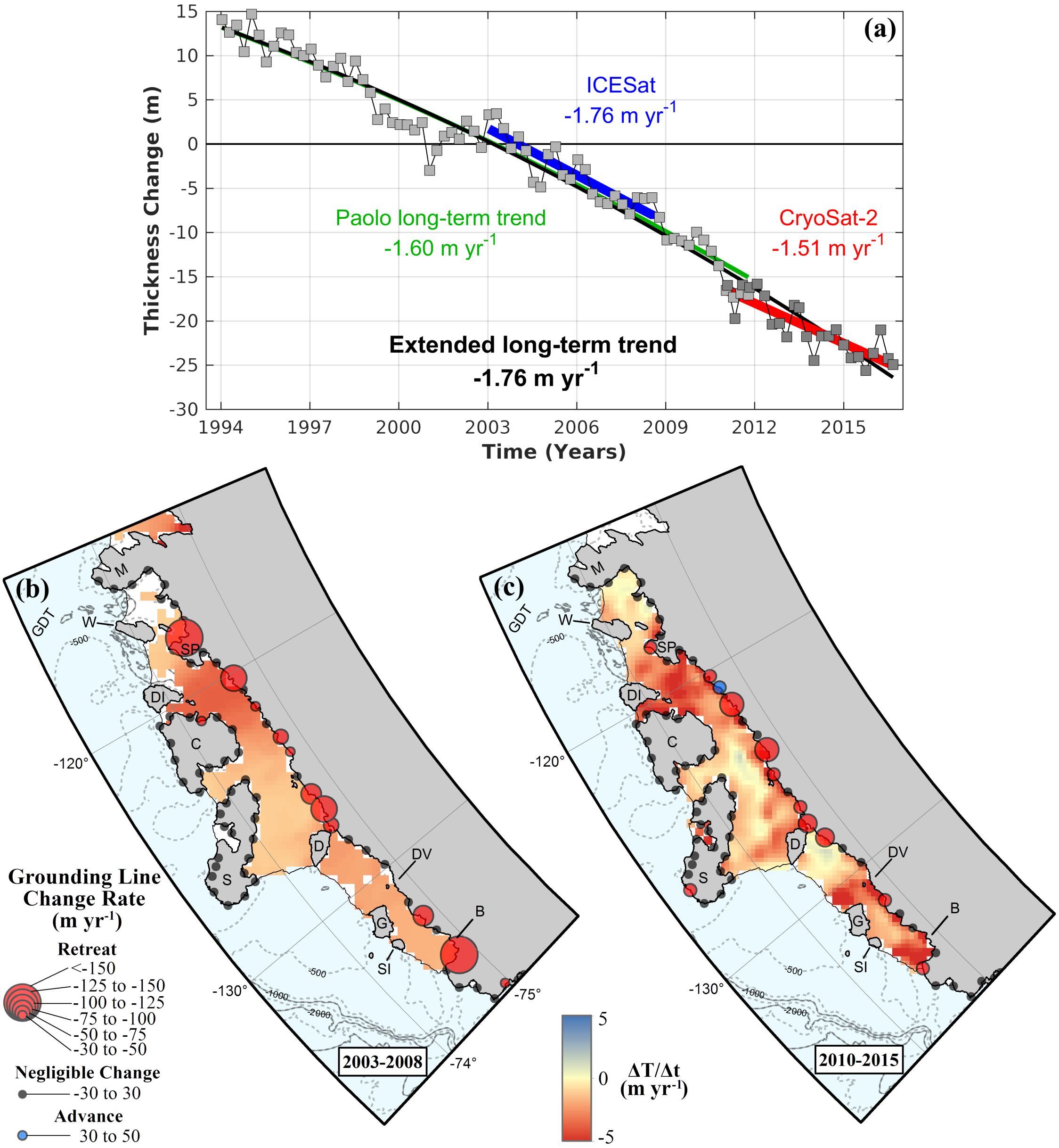

Figure 3. (*a*) Time-series of cumulative thickness change for Getz Ice Shelf, 1994-2016. Grey squares correspond to shelf-wide, 3-month-average thickness changes relative to the series mean, derived from ERS-1/2, ENVISAT (light grey squares; cf. Paolo et al. (2015)), and CryoSat-2 data (dark grey squares; this study). Black curve denotes the polynomial trend for the entire observational period (1994-2016), superimposed over the 1994-2012 trend (green line) reported in Paolo et al. (2015; their Fig. S1). Blue and red lines denote linear trends over the ICESat and CryoSat-2 eras, respectively. Average rates of thickness change (m yr^{-1}) were approximated from the derivative of the polynomial fit with respect to time. Whilst thinning rates during the CryoSat-2 era have not differed significantly from the ICESat and Paolo long-term trend, note the apparent hiatus in thickness change between 2011 and 2013, as discussed in Sect. 3.3 and 4.2.1. (*b*) and (*c*) Spatial distribution of Getz Ice Shelf thickness change rates (ΔTΔt; m yr^{-1}) over the ICESat and CryoSat-2 eras, respectively. For reference, GL change data from Fig. 2 are also shown. *SI* denotes Shepherd Island; all other site labels and bathymetric contours same as Figs. 1 and 2.

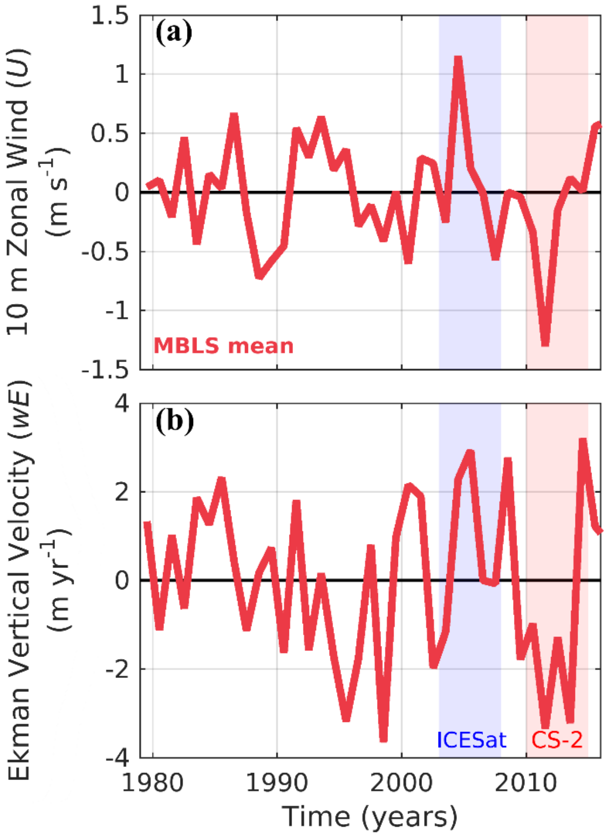

Figure 4. (*a*) Mean 1979-2016 10 m zonal wind (*U*) and (*b*) Ekman vertical velocity (*wE*) anomalies over the Marie Byrd Land Sector, derived from ERA-Interim climate reanalysis data. The blue and red patches denote the ICESat (2003 to 2008, inclusive) and CryoSat-2 (2010 to 2015, inclusive) eras where we have recovered grounding lines (Figs. 2a and b). *wE* anomalies were derived from the mean of all ERA-Interim grid cells located on the continental shelf, shelf break and shelf slope. *U* anomalies were averaged along the length of the continental shelf break and slope only (see also Fig. 6). In (*a*), positive values denote anomalous westerly 10 m surface winds; negative, easterly. In (*b*), positive values denote anomalous upwelling associated with Ekman Suction, and negative values denote reduced upwelling by Ekman Pumping. In (*a*) and (*b*), note the unprecedented MBLS *U* and positive *wE* over the ICESat era, compared with the strong negative anomalies during most of the CryoSat-2 era.

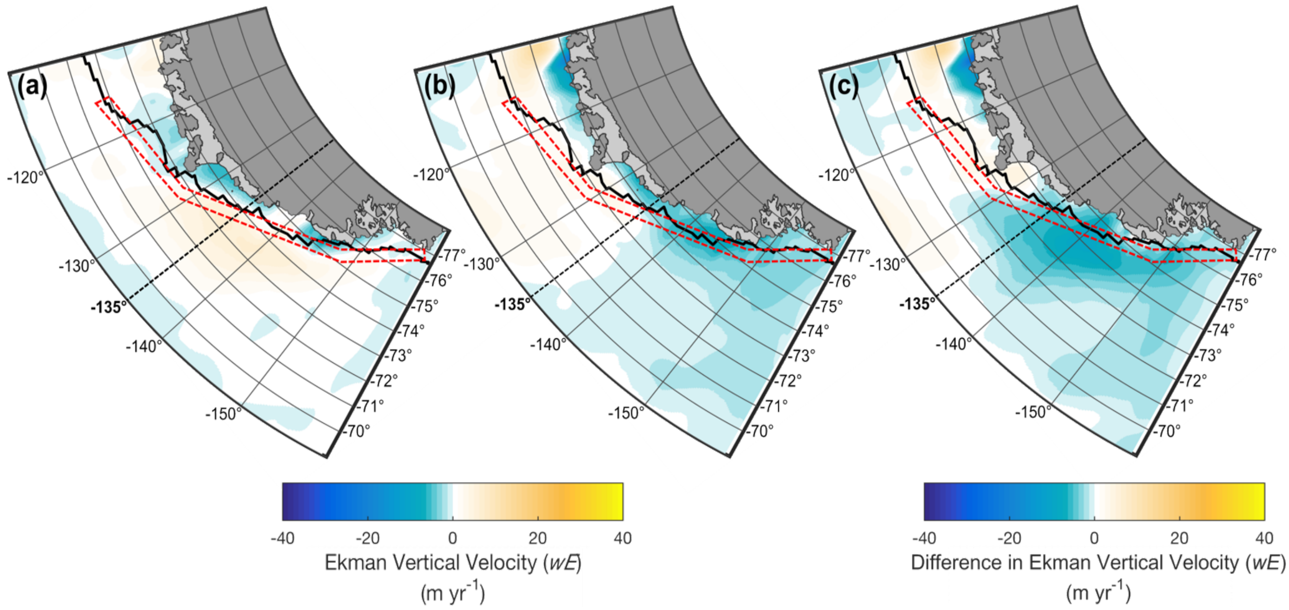

Figure 5. **Ekman vertical velocities (*wE*) for the period January 2003 to January 2008, inclusive (a), January 2010 to December 2013, inclusive (b) and their difference (c)** relative to all preceding years within the ERA-Interim record. Negative values denote **downwelling (a and b) or** reduced Ekman upwelling **(c). In all plots,** the thick black line denotes the approximate location of the continental shelf break at 1000 m depth (Arndt et al., 2013). The red dashed box**es** denote the region used to derive the mean MBLS 10 m zonal wind anomalies observed in Fig. 4a, and demarcates the northern-most limits of the grid used to derive the MBLS shelf-averaged *wE* anomalies shown in Fig. 4b. **In (c), n**ote the presence of deeply reduced upwelling near the ice-fronts of Dotson and Getz Ice Shelves at ~115° W, in addition to a similar phenomenon west of ~129° W which extends from the coastline to at least ~70° S. Opposite Getz Ice Shelf, also note the reduced *wE* near ~115° W, 70° S.

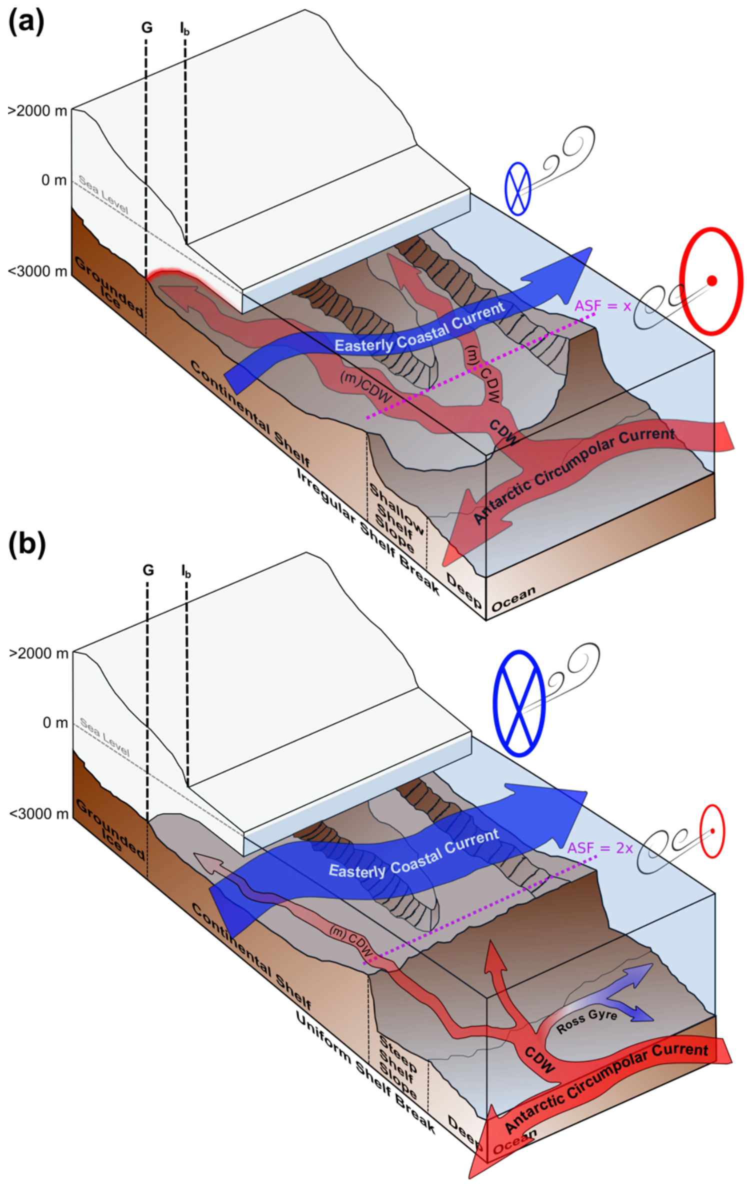

Figure 6. Schematic summary of the **oceanic, atmospheric** and geologic controls influencing glaciological change along (*a*) Getz Ice Shelf and (*b*) the region west of 135° W. In (*a*), the deep troughs bisecting the continental shelf break allow circumpolar deep water (CDW) to intrude onto the continental shelf and reach sub-ice-shelf cavities as modified CDW, enabling ocean-driven melting of ice and grounding line retreat. CDW is sourced from the Antarctic Circumpolar Current (ACC), located within close proximity to the shelf slope, and is transported upslope via surface wind-driven Ekman Suction, induced by anomalous westerly winds over the shelf break (see main text for further discussion). In (*b*), the steep continental shelf slope and shallow shelf break result in negligible or only minor access of CDW onto the continental shelf, associated with reduced eddy-mediated transport of CDW over the CSB, in conjunction with a stronger Antarctic Slope Front (ASF) than in (*a*) (Stewart & Thompson, 2015). **The northward deflection of the ACC, influenced by the easternmost limits of the Ross Gyre, also minimises the presence of CDW near the shelf slope**. Relative to (*a*), the strong easterly coastal current, comprising fresh Antarctic surface water (including Ross Sea-bound melt waters from Getz Ice Shelf and the wider Amundsen Sea Sector), acts to freshen the continental shelf water column (cf. Nakayama et al. 2014),

resulting in buffered modified CDW access to the sub-ice shelf cavity. G and I_b refer to the true grounding line and the ice-sheet-shelf margin inflexion point, respectively.