

Interactive comment on “Spatial and temporal variations in basal melting at Nivlisen ice shelf, East Antarctica, derived from phase-sensitive radars” by Katrin Lindbäck et al.

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Received and published: 19 July 2019

Dear Reviewer,

On behalf of all the authors of this discussion paper, I would like to thank you for your comments. Your suggestions have been acknowledged and have improved the paper substantially. Our responses can be found below.

Kind regards,

Katrin Lindbäck

RC1 General comments

C1

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In this manuscript, the authors use an exciting ApRES data set to investigate basal melt rates underneath the Nivlisen ice shelf, East Antarctica. While repeat measurements of 29 ApRES sites distributed across and along ice-flow direction result in only 'moderate (0.8 m/yr)' annual basal melt rates, continuous records from two ApRES sites reveal a seasonal signal with 'highest daily' basal melt rates of up to 5.6 m/yr near the ice front. This seasonal signal cannot be observed at the second continuous ApRES site further upstream, which leads the authors to conclude that the presence of warm ocean surface water in summer and its interplay with the dominant winds in the area is the cause for the increased melt, rather than the intrusion of circumpolar deep water that causes very high basal melt rates in other parts of Antarctica. The authors support their hypothesis with three GPR profiles, atmospheric data from both a nearby AWS and re-analysis data; and attempt the link of ApRES data to satellite imagery from MODIS.

In my opinion, the ApRES data set and the consequent quantification of basal melt rates in this area is required by the community to evaluate and improve current modelling efforts and I would very much like to see the manuscript published soon. The processing of the ApRES data is methodologically sound which makes this manuscript a valuable contribution to the study of ice-ocean interaction around Antarctica. I particularly enjoyed the thorough phase analysis between the two continuous ApRES records to display the seasonality in basal melting. The manuscript is mostly well organized but: (1) some parts of the extensive discussion can be shortened and belong to the description of the study area. Similarly, the writing style can be improved in many places. (2) The link to satellite data that is even underlined in the conclusion is weak which doesn't align with the author's very elegant analysis of ApRES data. (3) Some statements about the present pinning-points and their effect on ice-shelf stability can't be made with the data set presented. I recommend the manuscript for publication after minor revisions that include a revisit to the last part of the discussion section. I'm looking very much forward to it.

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Author response:

We are very grateful for your positive review. We have taken into account all your main suggestions and detailed responses can be found below.

RC2 Minor comments

RC2.1

I. 29-30: Including a statement about pinning points and their stabilizing effect made me anticipate a corresponding analysis in the main text. Without this analysis the statement is a bit too speculative to be included in the abstract. Reword

Author response:

We have removed the sentence in the abstract.

RC2.2

I. 35-36: I think with 'shrinking' you mean 'thinning'. I suggest changing to '...thinning glaciers in West Antarctica that lost back-stresses from their buttressing ice shelves.'

Author response:

We have changed the wording as suggested.

RC2.3

I. 40-41: Change 'input of grounded ice upstream' to 'from ice across the grounding line' as it is a flux-gate calculation at the boundary between floating and grounded ice. Include 'underneath the floating ice shelf' after 'ocean' and 'at the ice front' after 'calving'. Also surface mass balance can be negative and represent ice loss. Please include in this list.

Author response:

We have rewritten the sentence as suggested.

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RC2.4

I. 43: Change to '...stresses on grounded ice upstream, leading the tributaries to flow faster' as there are more than one stress component to provide buttressing.

Author response:

We have rewritten the sentence as suggested.

RC2.5

I. 45: Change to 'therefore the key to gain a : : '

Author response:

We have rewritten the sentence as suggested.

RC2.6

I. 52,62,75: I like the review of Jacobs melt modes and its link to basal melting around Antarctica. However I had to read these three paragraphs twice to follow. Reword to 'In mode 1, : : ' then 'In mode 2, : : ' and 'In mode 3, : : ' each followed by examples from the literature to help the reader. How about the high melt rates that have been observed in basal channels and lake drainage on Roi Baudouin or underneath the Whillans Ice Stream ? Please include in this review section.

Author response:

We have restructured the section as suggested. We have added a reference to Whillans Ice Stream about high melting at basal channels. We did not include surface melting from Roi Baudouin, but it is reviewed in the Study area section

RC2.7

I. 68: Change to 'Totten'

Author response:

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We have corrected the typo.

RC2.8

I. 81-82: This is hard to read. Change to '...reflect the integrated response to changes in circumpolar deep water temperatures and coastal processes that control its access onto the continental shelf (Thompson et al., 2018)' and please remove 'and the local upper ocean heat supply' as it doesn't add anything to the sentence.

Author response:

We have changed the sentence as suggested.

RC2.9

I. 99: Change 'resolution' to 'accuracy' or do you really mean vertical spatial resolution here ? Also change 'over' to 'and'

Author response:

We have changed the words as suggested.

RC2.10

I. 104: Change 'explain' to 'interpret' as you only analyse the data at this section of the paper.

Author response:

We have rephrased the sentence as suggested.

RC2.11

I. 106: Change 'were' to 'are'. General convention is to use past tense for everything that was done and present tense for everything that you have found out.

Author response:

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We have changed the tense.

RC2.12

I. 107: Change to 'complement' as your data is plural

Author response:

We have corrected the typo.

RC2.13

I. 108: Change to 'data source'

Author response:

We have changed as suggested.

RC2.14

I. 112-113: Remove the first sentence as it doesn't add to the paper.

Author response:

We have removed the sentence.

RC2.15

I. 117: Change to 'Basal melt rates from satellite data in: : ':' to avoid the long concatenation

Author response:

We have changed the sentence.

RC2.16

I. 121-124: Remove '100 km...ponds.' as this is trivia in the context of the paper.

Author response:

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We have removed the section.

RC2.17

I. 125-126: Change to ': : : has an estimated potential of raising global sea level by 8cm.'

Author response:

We have changed the sentence.

RC2.18

I. 132: you haven't introduced/defined the grounding zone yet. What do you mean exactly or can 'in the grounding zone' be removed ? For me a grounding zone is caused by tidal variability of ice mechanics downstream of the grounding line where ice detaches from the bed and becomes afloat.

Author response:

We have added a definition of the grounding line/zone, where the term is first introduced.

RC2.19

I. 136: Change 'the shelf' to 'its stability'

Author response:

We have changed as suggested.

RC2.20

I. 146: Include 'gradients' or 'heterogeneity' after 'surface mass balance'

Author response:

We have added the word 'gradients'.

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RC2.21

I. 148: again 'in the grounding zone'

Author response:

We have added a definition of the grounding zone earlier in the text.

RC2.22

I. 157: Change '...remaining 25% coming from...' to '...residual 25% attributed to : : ' to avoid colloquial language

Author response:

We have changed the sentence.

RC2.23

I. 158-165: This would be very interesting to see in your Fig. 1B (see specific comment below)

Author response:

We have not included the carbon dating sites in the figure, since there were several of them and they were not part of this study.

RC2.24

I. 170: Remove 'summertime' and change 'minimum to 'minima' as you also you 'maxima' earlier

Author response:

We have corrected the word.

RC2.25

I. 172: Reword 'dominant modes' as you introduced Jacobs modes earlier and you

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don't want to confuse the reader with additional modes

Author response:

We changed the word 'modes' to 'trends'.

RC2.26

I. 177: Change 'then' to 'consequent'

Author response:

We have changed the word.

RC2.27

I. 178: Change to 'remains'

Author response:

We have corrected the typo.

RC2.28

I. 181-183: Include 'the' before 'Antarctic' and 'end'. The sentence about logistical support can be removed (you have it in the Acknowledgements already)

Author response:

We have corrected the text, but would like to keep the station description in the text. We have removed the reference in the Acknowledgements.

RC2.29

I. 185-186: Remove 'Below,...melt rates' as it doesn't add to the paper

Author response:

We have removed the sentences.

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RC2.30

I. 187: Change 'studied' to 'measured'

Author response:

We have changed the word.

RC2.31

I. 189: Include 'all 29' after 'measured at' and change 'stake locations' to 'ApRES sites'

Author response:

We have changed the wording.

RC2.32

I. 190: Change to 'Autonomous phase-sensitive Radio Echo Sounder'

Author response:

We have changed the heading.

RC2.33

I. 191: Change 'speed' to 'velocity' as you mention the calculation of strain rates which require a direction. Velocity is speed with direction, speed doesn't have a direction. I.

Author response:

We have changed as suggested.

RC2.34

I. 193: Change 'shelf' to 'flow'

Author response:

We have changed the word.

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RC2.35

I. 195-196: 'Ice tongue' is this a common expression for this particular part of the ice shelf ? For me an ice tongue is a glacier that sticks out into the ocean without lateral thinning (for example the Drygalski Ice Tongue) and not a part of the floating ice shelf that is pushed through two ice rises like the one here.

Author response:

We have removed 'ice tongue' from the manuscript.

RC2.36

I. 200 and elsewhere: 'stake sites' is confusing. Please reword throughout the paper

Author response:

We have changed 'stake sites' to 'ApRES sites'.

RC2.37

I. 217: Remove one of the two 'that'

Author response:

We have corrected the typo.

RC2.38

I. 223-226: Reword this very long sentence. Also the word 'both' is used two times (the first one refers to actually three nouns). Maybe break it up into two sentences.

Author response:

We have rewritten the sentence into two.

RC2.39

I. 233: Change 'returns' to 'reflector' and start a new sentence after 'processing' with

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'This allowed us to : :'

Author response:

We have changed the sentence as suggested.

RC2.40

I. 236: The 36 h window size needs explanation.

Author response:

To get the mean melt rate, we needed to remove the time-average strain rate, which we needed to calculate elsewhere, essentially by comparing vertical profiles throughout the time series to see how the internal reflectors move with respect to each other. That correction sets the level of the melt rate. After that we assume that the main remaining vertical strain signal that needs to be removed is from tidal variation in the semi-diurnal and diurnal bands. So instead of trying to calculate the vertical strain rate at tidal frequencies (very difficult to do precisely because of the weakness of the internal reflections) we throw out all tidal variability (melt and strain) by filtering at 36 hours. That leaves us with the variability of most interest here. The assumption is that there is no significant tidal strain at frequencies slower than diurnal, except for the constant background strain rate. In some large ice shelves, a fortnightly signal is visible in the vertical strain rates, as a result of non-linear interactions between the diurnal and/or semidiurnal tides. That signal was not strong at these sites. We have clarified this in the text.

RC2.41

I. 241: Include 'also' after 'we'. Sounds like 2016 was a busy field season !

Author response:

We have included the word as suggested.

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RC2.42

I. 242: Remove 'across...structure' and replace with '...measurements on Nivlisen ice shelf (profiles A,B and C in Fig. 1b) as you have mentioned the orientation of the profiles already.

Author response:

We have changed the sentence as suggested.

RC2.43

I. 246: there are three times the word 'with' in one line. Please reword

Author response:

We have rephrased the sentence as suggested.

RC2.44

I. 248: Replace 'traces' with 'measurements'. Is 'code-phase' GPS special and improves your accuracy ? If it isn't I suggest removing it

Author response:

We have changed the words, however, we have kept the 'code-phase' description since it is a different GPS than the 'carrier-phase', which has better accuracy.

RC2.45

I. 260-262: This sounds strange. Why is there such a big difference between the two methods to determine firn depth ? Also why is this important ? Did you use a 2-layer velocity model to convert travel time to depth ? I assume not. How did you determine 50 m firn from the ApRES data you present in Fig. S1 ? Please add some information here.

Author response:

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We added a plot to Figure S1, where we show how the assumption of 50 m firn depth was made. We did not use a 2-layer velocity model, since it was not necessary for the purpose of this study, and the density error is included in the uncertainty number.

RC2.46

I. 262-263: Please add a sentence why the calculation of ice draft is necessary in this context. Also, for your freeboard calculation you require a sea level right ? Where does this come from ? A geoid model ?

Author response:

We have added a sentence why ice draft is important and added information about the geoid.

RC2.47

I. 274: Remove 'We...Nivlisen.' as it doesn't add to the paper and is mentioned in Data and Methods section already

Author response:

We have removed the sentence.

RC2.48

I.281: Change 'speed' to 'velocity'

Author response:

We have changed the word.

RC2.49

I. 294: Again 'melt rates at stake locations'. Please reword

Author response:

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We have changed it to 'ApRES sites'.

RC2.50

I. 294,296,297: It's called 'average annual'

Author response:

We have changed it to 'averaged annual' throughout the manuscript.

RC2.51

I. 299-300: Reword and start the sentence with 'In 2018' to conform with the start of the paragraph

Author response:

We have reworded the sentence.

RC2.52

I. 304: 'low strain rates' compared to what ? Please add

Author response:

We have removed the statement.

RC2.53

I. 314: somewhere around here you move from using 'basal melt rates' to only 'melt rates'. Please remain consistent

Author response:

We have added 'basal' to 'melt rates' in many places throughout the manuscript.

RC2.54

I. 315: Include 'as' after the comma

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Author response:

We have corrected the sentence as suggested.

RC2.55

I.316 and elsewhere: your 14 moth record ends in 2018 and not in 2017. Please change here and also in Figure captions.

Author response:

We have corrected the typo, here and in the figure captions. Thanks for noticing.

RC2.56

I. 461-473: Most of this belongs to Section 2 Study Area where you explain the oceanographic setting. Please move this paragraph, but still discuss earlier studies in a 'this confirms/is against the findings of way" at this stage.

Author response:

We have moved the paragraph to the Study area.

RC2.57

I. 503-504: Same here, move to Section 2

Author response:

We have rephrased the sentence. The statement is mentioned in the Introduction.

RC2.58

I. 511-517: This is a nice paragraph and should also discuss potential links to Stewart et al., 2019. Is this the same mechanism at play ?

Author response:

We have added a paragraph comparing with Stewart et al. (2019). In similarity with

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our study they find a link to solar-heated surface water, but they did not find any link to downwelling-favourable winds.

RC2.59

I. 521: Change 'Fig. 7d' to 'Fig 7c'

Author response:

We have corrected the figure number.

RC2.60

I. 531-532: This statement needs to be defended with the right figure ! I suggest to change Fig. 7 (see below)

Author response:

We have updated Fig. 7 and also added a figure (Fig. 8) from the Supplements to support this statement.

RC2.61

I. 533: Reword to '...was pushed by wind under the front of Nivlisen ice shelf'

Author response:

We have changed the sentence as suggested.

RC2.62

I.534-539: I would swap these two sentences and begin with 'Surface wind' then say something about 'Surface warming' to get the order of processes right. End this paragraph here and remove the last sentence 'Natural...sea ice' as this more general statement that doesn't really fit here and creates an impression that actually weakens your results.

Author response:

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We have rearranged the sentences and removed the last sentence as suggested.

RC2.63

I. 548,551: Add values (0.8 and 5.6 m/yr) in braces after 'moderate' and 'summer'. Also add 'relatively' before 'high melt rates' as 5.6 m/yr are not high melt rates when I think of the Amundsen Sea.

Author response:

We have added the numbers to the conclusions.

RC2.64

I. 549: 'Daily' ? As far as I thought the temporal resolution of the data is much higher. More information is required on how you acquired the continuous ApRES data. Number of bursts/averaging/etc

Author response:

We have changed 'daily' to 'hourly'.

RC2.65

I. 558: Change 'of' to 'in'

Author response:

We have changed the word.

RC2.66

I. 559: Include 'temporally' before 'higher'. Also be consistent with 'basal melt rates' as it is called here 'rates of melting'

Author response:

We have changed as suggested.

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RC2.67

I. 564-565: Again 'pinning points'. I don't think that there is enough analysis on their stability and how this might be affected by your measurements to include a statement like this in the conclusion. Please reword or move this to the discussion.

Author response:

We have moved this section to the discussion.

RC2.68

I. 570-571: Change 'important' to 'crucial' and remove 'which in turn is important for ice sheet models' as understanding the driving mechanism is much more important than including it into a model. By removing the last bit you put more emphasis on this.

Author response:

We have changed the sentence as suggested.

RC3 Specific comments throughout the paper

RC3.1

1. hyphenations in compound expressions are sometimes wrong or missing. For example I.131 'ice-shelf flow'. Hyphenation is wrong if no noun follows: 'the ice shelf flows' versus 'the ice-shelf flow'

Author response:

We have corrected this at several places and will check this in detail once more for the final version of the paper.

RC3.2

2. 'Stake locations' I know that this comes from locating the ApRES antennas in the field over several years but somehow it sounds like you measure basal melting with

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stakes only. Can you reword 'Stake locations' to 'ApRES sites' and mention stakes only where you use them for the GPS survey and strain calculation ?

Author response:

We have changed 'stake locations' to 'ApRES sites'.

RC3.3

Figures: Figures are all way to small (see individual comments below)

Author response:

Figures are not allowed to have full width in the pdf-version of the paper. We have increased the size of the text and it is possible to click and zoom in the figures online. We will check this again in detail before the final version.

RC3.4

Fig. 1) (a) what is the gray shaded area in the lower right ? (b) The ice-shelf front and the Landsat mosaic don't match up. Why is approx 1/3 of the ice shelf missing? I suggest replacing the Landsat part of the figure with a schematic of what you know about the bathymetry (ridges, troughs, continental shelf edge) and the dominant oceanographic currents as you describe nicely in the main text (l. 158-165). Where was the carbon dating site ? Maybe remove the 'Ice structure' as you don't refer to them in the analysis of profile A-Aprime. (caption) Change 'made' to 'located'

Author response:

The figure has been updated with elevation contours to show bathymetric ridges and the continental shelf edge. The ice-shelf front is outlined with a contour as described in the legend, were the Landsat image also shows sea ice north of the ice front. We have clarified this in the figure caption. We would like to keep the ice structure, since it shows ice-shelf characteristics. We have not added the carbon dating sites, since there were many sites and they were not part of this study. We have removed the grey

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shaded area in Fig. 1a. We have reworded the figure caption as suggested.

RC3.5

Fig. 2) (a) colorbar for REMA DEM is missing, I like the absolute values of basal melt rates. (b) plot the difference of your GPR measurements to the Bedmap2 product and replace the colorbar with the new values. The contours stay the same, but you can tell where they match and where they don't. (c) similar here, color-code the stake sites with the difference to Measures and annotate the absolute measured value of Ice flow velocity. (d) Same here, I'd display the difference in the markers and write the absolute measured SMB next to the stake sites. (caption) remove 'hill shade'

Author response:

We have updated the figure as suggested with difference between the in situ measured values and satellite or modelled. We removed the REMA hillshade in Fig. 2a since it was difficult to interpret.

RC3.6

Fig. 3) Font size is incredibly small! First remove all repeated text from each of the three subplots. Each of the individual panels of the subplots use the same Distance so you only need to display that at the lower panel. The x-axis label 'Distance (km)' only needs to go below the third subplot. Also, all three surface elevation panels should have the same yaxis limits to be comparable. The radargram in the middle misses the blue surface elevation curve.

Author response:

We have updated the figure as suggested. We would like to keep the distance as it is for Profile B and C, since then it is possible to see details like the basal channels, which would not be possible if the profile was the same scale as the very long Profile A.

RC3.7

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Fig. 4) (a) the start of the gray box c doesn't match with the start of your third subplot. (b) what do the white shaded areas in lower left and right mean ? (c) good (d) You don't need to write 'Time' when it is clear from the xaxis ticklabels. Maybe change 'Time' to '2017' (caption) the first 2017 is a 2018, right ? Ylabels 'melt rate' versus 'basal melt rate' earlier, pick one.

Author response:

We have improved the figures as suggested. The grey shaded areas in the lower left and right are the cone of influence, where edge effects become important and the image can be distorted. We have clarified this in the figure caption

RC3.8

Fig. 5) (a) Consider writing '2017' and '2018' left and right next to the gray bars. (b and c) good (d) This looks like a spring-neap tidal signal over 14 days. Xticklabels should be the same as for Fig 4d. Consider replacing 'Time' with '2017'

Author response:

We have improved the figures as suggested.

RC3.9

Fig. 6) Very nice plot ! Don't use the same colormap as for Figs 4b and 5b as this is a different variable. Consider including a Legend with the arrow directions and 'in phase', 'seawards leads' and 'landward leads'. What do arrows pointing left stand for ? Also, has there been a threshold in coherence when you display the arrows ? What are the shaded areas in lower left and right ?

Author response:

Thanks! We have changed the colour map and inserted a legend with the arrows as suggested. Within the cone of influence, shown as a lighter shade, edge effects become important and the image can be distorted. We have clarified this in the figure

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caption.

RC3.10

Fig. 7) I think this plot doesn't really show what you say in the main text. Both the temperature and sea-ice cover subplots didn't really help my understanding and could be moved to the supplements. Also, the interpretation of using dashed lines is too subjective to say that satellite data can't capture high melt events. I suggest: (I) using the space of subplots c and d and replace with a scatterplot of summertime wind speeds vs basal melt rates on the seaward site, where the dots are color-coded to wind direction (similar to Fig. S5). (II) shade areas in (a) when you see open water in satellite data. Has the time lag between peaks in wind and basal melt rate only been estimated from the dashed lines? That's ok, but it must be stated in the main text. (caption) Include 'nearby' before 'weather station'

Author response:

We have updated the figure as suggested and added a shaded grey area for the time period of open water. We added an updated version of Fig. S5 from the supplements as Fig. 8. We have clarified in the text that the dashed lines are where the time lags have been calculated.

RC3.11

Fig. S1) I can't see how a firn depth of 50m is derived from this plot, where does it come from and why is this important? Change xaxis label to 'Depth below surface (m)'

Author response:

We have added a subplot with the residual height to show the assumption about the firn depth. We changed Depth to Range.

RC3.12

Fig. S2) Comparing (c) to (d) indicates that there was less melt in 2018.

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Author response:

We have added a sentence in the caption from the results: “Basal melt rates were slightly lower in the second year at 18 sites and for 8 sites slightly higher.”

RC3.13

Fig. S3) (a) yaxis label is missing (b) include two xaxis labels '2017' and '2018'

Author response:

We have adjusted the labels as suggested.

RC3.14

Fig. S4) good

Author response:

Thanks!

RC3.15

Fig. S5) (caption) Change '2017' to '2018'

Author response:

The figure was moved to the manuscript as Figure 8. The figure shows scatter plot between overlapping time periods when there was open water (11 Dec 2016-1 Mar 2017).

RC3.16

Fig. S6) can you include the information about open water availability in your analysis?

Author response:

We have included this in the Discussion section.

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