The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2019-108-AC1, 2019

The Cryosphere
Discussions
Open Access

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.

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

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Discussion paper

RC1.1

This paper presents new measurements of sub-shelf melt rates of Nivlisen Ice Shelf in Dronning Maud Land, acquired with ApRES. The survey includes measurements across a broad area of the shelf at yearly resolution and at two points with 36-hour resolution, allowing the authors to study both spatial and temporal variations in melt. The melt rates on Nivlisen are found to be relatively modest, with the highest melt rates in the summer and just behind an ice rumple. These melt rate measurements are compared to a common-offset radar survey of ice-shelf thickness and to atmospheric data. While there is no correlation between ice-shelf thickness and melt rates, the atmospheric data suggest that the highest melt rates may be caused by wind pushing warm surface waters beneath the shelf.

The acquisition of ApRES data to determine melt rates is highly valuable as it allows direct measurement of ice-thickness changes while removing assumptions about firn thickness, strain rates, and/or hydrostatic equilibrium that affect other techniques. The authors have done a careful job in processing the data and assessing the uncertainty in the measurements, and performed extensive and detailed analysis of those results. Relatively few studies have used pRES on ice shelves, and the precision, temporal resolution, and relatively large spatial extent of these measurements make this paper a valuable insight into processes controlling melt, particularly beneath East Antarctic ice shelves. I have a number of comments, primarily focusing on the presentation and discussion, but I think the paper is a nice contribution and will soon be suitable for publication in The Cryosphere.

Author response:

Thanks for your positive comments, very much appreciated!

RC1.2

The lengthy discussion of Jacobs et al.'s melt modes is too meandering to be easily followed. If this section is retained, I would recommend restructuring to introduce all 3 melt modes with brief definitions first before going on to detail each. In the conclusion, where mode-2 is mentioned again after having been absent since the introduction, it needs redefining. However, I do not find this division of modes to a very clean distinction for the purposes of this study. Instead, perhaps simply say that melt can be driven either by warm summer water near the surface or by warm water at depth and provide citations for each.

Author response:

We have restructured the section about the melt modes, clearly starting with each mode and its definition.

RC1.3

It seems like a stretch to call 4 m/yr "high" melt given the rates observed in West Antarctica. Sometimes this melt is described as "high" and sometimes as "higher"- I think remaining consistent calling it "higher" would be most clear.

Author response:

We have changed "high melt" to "higher melt" throughout the manuscript.

RC1.4

The distinction between high melt and melt that is in excess of steady state gets a bit muddled here, partly because of the repeated use of the phrase "mass loss" to mean an outgoing flux of ice rather than a loss of total ice volume. I would suggest other terminology, such as "outgoing flux" or something similar, so as to clearly distinguish from a net loss. While I can figure out what is intended, I find the phrasing particularly distracting in the discussion of iceshelf stability, since the measurements all indicate the melt rates at a particular, with no clear measure of whether those rates are sustainable or "normal". This ambiguity extends into the conclusionsâĂŤmost of the second paragraph of the conclusions is not a conclusion of this work, but more-or-less a hypothesis that “mode-3” melt may affect the stability of some ice shelves. It is fine/good to make this argument, but I would not consider it a conclusion of this work and would find this paragraph more appropriate merged into the last section of the discussion (and perhaps reiterated in a single sentence in the conclusion).

Author response:

We have changed the term “mass loss” to “stability”. We have also moved the paragraph in the conclusions to the discussion. We hope is clearer now the distinction about the current status and potential future change.

RC1.5

In section 5.2, it would be nice to see a bit more connection between the different paragraphs. There is a lot of nice, detailed analysis of the phases and spectral power of the melt, but it is hard to know what to make of it in the aggregate. At present, the summary paragraph at the end of this section really just focuses on wind; it would be a huge help to use this paragraph to explain how the phase lead/lag of the seaward/landward sites can be related to the wind forcing, and to whether the spectral power of the melt at each site individually tells us anything about the validity of these conclusions.

Author response:

We have rewritten the last paragraph in the discussion give a better overview.

RC1.6

All figures except Figure 1 should be enlarged. Simply expanding them to take up the full-page width would help significantly. Even with that expansion, though, some text needs to be further enlarged.

Author response:

The figure size is fixed to a certain width by TC, if we understood it correctly, and cannot be set by us to fill the full-page width in a pdf. We have, nevertheless, enlarged the text in the figures to make it more readable and will do a final check before publication to make sure it looks ok.

RC2 Specific comments

RC2.1

L41: For Nivlisen, surface melt/sublimation must be included in the inputs and outputs

Author response:

We have added surface melting and sublimation to the sentence.

RC2.2

L49: Even though Rignot et al. state something similar this, I think this mischaracterizes the results of those studies; they both show calving and melt are equal within error.

Author response:

We have rephrased the sentence as suggested (melt and calving equal).

RC2.3

L56: This sentence needs the context that this is the mode affecting the largest shelves

Author response:

We have clarified that this affects the largest ice shelves.

RC2.4

L75: What do you mean by “only recently”? Is this a change in occurrence or in observability? Why does this recentness suggest that it is important?

Author response:

We have removed “only recently”.

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Discussion paper

RC2.5

L121-124: Is the inland geography relevant anywhere in the rest of the paper? I think this can be removed

Author response:

We have removed the sentences.

RC2.6

L129: Maybe move ice rise/rumple definition to where they are introduced in L114.

Author response:

We have moved the definition to the suggested section.

RC2.7

L160: Would be clearer to say “the ice front retreated to its present position by $\sim$11 kyr ago”

Author response:

We have rephrased the sentence as suggested.

RC2.8

L162-165: The wording here makes the meaning unclear - is the entrainment in line 163 the same as in 165, or are two different processes being described? In line 163, the reader needs to know what the CDW is being entrained into.

Author response:

The water is entrained into the Antarctic slope current. We have clarified the sentence.

RC2.9

L198: Maybe mention the battery capacity here, since I’m sure others are considering similar deployments

Author response:

We have included the battery capacity.

RC2.10

L237-239: I'm not entirely clear what is meant here. You assume that strain varies either on very long timescales or on timescales shorter than 36H but not in between âĂŤessentially a bandstop filter? Are variations with the frequency of other tidal components small?

Author response:

This is not actually a bandstop filter. 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.

RC2.11

L271: Do you mean that the effect of horizontal positioning on the error in the vertical is 0.1$\pm$0.2 m?

Author response:

Yes, we have clarified this in the text.

RC2.12

L278: Citation for CSRS-PPP? Static or kinematic processing?

Author response:

We have added a reference to the processing and stated that it is static processing.

RC2.13

L299-301: I'm guessing you exclude the sites near the ice rumple because you were unable to revisit them? Perhaps mention this explicitly here.

Author response:

We have added a sentence clarifying this as suggested.

RC2.14

L340: Can you say definitively that Bedmap2 is too high or could the thickness have changed?

Author response:

Bedmap2 is 50-100 m off in this area and indicates an ice-rise like feature that cannot be seen in neither our radar data, our GNSS data nor the new REMA product. The ice-shelf is very flat in this area and a major change over the last few decades is unlikely. We edited the related sentence in the paper as follows: "The broad thickness pattern agrees with the gridded ice thickness of Bedmap2 (Fretwell et al., 2013), except on the western ice tongue (profile C), where the thickness of Bedmap2 is clearly too high (Fig. 2b), possibly due to errors in the input data or the interpolation between them."

RC2.15

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L362-364: This sentence seems a bit backwards to me, but I know little about vorticity waves - can you clarify the mechanism for reducing melt rates and restructure the sentence so that cause and effect are clear?

Author response:

We have rephrased the sentence and left out the term “vorticity waves” and just described the strong tidal currents in shallow regions (thin water column thickness) around the ice rise that may increase the ice-ocean heat exchange.

RC2.16

L370-372: The language here should be made clearer. The measurements seem to indicate near perfect balance, so why would anything happen as a result of these rates being sustained?

Author response:

We have rephrased the sentence and replaced “sustained high melt rates” with “an increased basal melting in the future”.

RC2.17

L559: Based on the evidence provided in the paper, it would be more appropriate to say that the melt rates are susceptible rather than that the ice shelves are susceptible.

Author response:

We have removed the word “susceptible” in the sentence.

RC2.18:

Figure 2: The color scales should be changed to match between the point measurements and the rasters in b-d.

Author response:

We have updated the figure as suggested by Reviwer #2, with difference between the in situ measured values and satellite or modelled values. The measured values are kept as numbers.

RC2.19

Supplementary Figure 1: Why is the x-axis in panel a in meters after a Fourier transform? Should it not be in Hz, or is this not the transformed data?

Author response:

For a FMCW radar, the frequency of each component of the data that are acquired represents the range to a reflector via the formula $R = T \cdot f \cdot v\_i/(2 \cdot B)$, where v_i is the radar speed in ice, f is the frequency associated with the reflection at range R, T is the length of the chirp in seconds, and B is the bandwidth of the chirp. So we have taken the Fourier Transform, and converted to range using the above formula. We have clarified this in the figure caption.

RC3 Technical corrections

L36: shrinking suggests extent, thinning would be more appropriate

L68: Tottem => Totten

L98: subject/verb disagreement

L103: “to explain them using” is an awkward phrase here

L154-155: This sentence needs a subject

L253: Line spacing of 5 km? Trace spacing of 5 m? I think there is a typo here.

L296: close to => just upstream of?

L305: average rate of thickness change

L561: there is a typo somewhere in “may increase leading”

L566: The first comma should not be there Author response

Author response:

We have corrected all these errors. Thanks for pointing them out!

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-108, 2019.

The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2019-108-AC2, 2019

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Kind regards,

Katrin Lindbäck

RC1 General comments

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.

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

l. 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

l. 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

l. 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.

RC2.4

l. 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

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

Author response:

We have rewritten the sentence as suggested.

RC2.6

l. 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

l. 68: Change to 'Totten'

Author response:

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We have corrected the typo.

RC2.8

l. 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

l. 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

l. 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

l. 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:

We have changed the tense.

RC2.12

l. 107: Change to ’complement’ as your data is plural

Author response:

We have corrected the typo.

RC2.13

l. 108: Change to ’data source’

Author response:

We have changed as suggested.

RC2.14

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

Author response:

We have removed the sentence.

RC2.15

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

Author response:

We have changed the sentence.

RC2.16

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

Author response:

We have removed the section.

RC2.17

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

Author response:

We have changed the sentence.

RC2.18

l. 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

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

Author response:

We have changed as suggested.

RC2.20

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

Author response:

We have added the word 'gradients'.

RC2.21

l. 148: again 'in the grounding zone'

Author response:

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

RC2.22

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

Author response:

We have changed the sentence.

RC2.23

l. 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

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

Author response:

We have corrected the word.

RC2.25

l. 172: Reword 'dominant modes' as you introduced Jacobs modes earlier and you don’t want to confuse the reader with additional modes

Author response:

We changed the word ‘modes’ to ‘trends’.

RC2.26

l. 177: Change ’then’ to ’consequent’

Author response:

We have changed the word.

RC2.27

l. 178: Change to ’remains’

Author response:

We have corrected the typo.

RC2.28

l. 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

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

Author response:

We have removed the sentences.

RC2.30

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

Author response:

We have changed the word.

RC2.31

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

Author response:

We have changed the wording.

RC2.32

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

Author response:

We have changed the heading.

RC2.33

l. 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. l.

Author response:

We have changed as suggested.

RC2.34

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

Author response:

We have changed the word.

RC2.35

l. 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

l. 200 and elsewhere: ’stake sites’ is confusing. Please reword throughout the paper

Author response:

We have changed ‘stake sites’ to ‘ApRES sites’.

RC2.37

l. 217: Remove one of the two ’that’

Author response:

We have corrected the typo.

RC2.38

l. 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

l. 233: Change ’returns’ to ’reflector’ and start a new sentence after ’processing’ with

’This allowed us to: : :’

Author response:

We have changed the sentence as suggested.

RC2.40

l. 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

l. 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

l. 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

l. 246: there are three times the word ’with’ in one line. Please reword

Author response:

We have rephrased the sentence as suggested.

RC2.44

l. 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

l. 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:

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

l. 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

l. 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

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

Author response:

We have changed the word.

RC2.49

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

Author response:

We have changed it to ‘ApRES sites’.

RC2.50

l. 294,296,297: It’s called ’average annual’

Author response:

We have changed it to ‘averaged annual’ throughout the manuscript.

RC2.51

l. 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

l. 304: ’low strain rates’ compared to what ? Please add

Author response:

We have removed the statement.

RC2.53

l. 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

l. 315: Include ’as’ after the comma

Author response:

We have corrected the sentence as suggested.

RC2.55

l.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

l. 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

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

Author response:

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

RC2.58

l. 511-517: This is a nice paragraph and should also discuss potential links to Steward 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 our study they find a link to solar-heated surface water, but they did not find any link to downwelling-favourable winds.

RC2.59

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

Author response:

We have corrected the figure number.

RC2.60

l. 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

l. 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

l.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:

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

RC2.63

l. 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

l. 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

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

Author response:

We have changed the word.

RC2.66

l. 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.

RC2.67

l. 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

l. 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 l.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

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 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

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 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 to 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.

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.

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-108, 2019.

Spatial and temporal variations in basal melting at Nivlisen ice shelf, East Antarctica, derived from phase-sensitive radars

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Abstract

Thinning rates of ice shelves vary widely around Antarctica and basal melting is a major component in ice shelf mass loss. In this study, we present records of basal melting, at unique spatial and temporal resolution for East Antarctica, derived from autonomous phase-sensitive radars. These records show spatial and temporal variations of ~~ice shelf~~ basal melting in 2017 and 2018 at Nivlisen ice shelf, central Dronning Maud Land. The annually averaged basal melt rates are in general moderate (~0.8 m yr^{-1}). Radar profiling of the ice-shelf shows variable ice thickness from smooth beds to basal crevasses and channels. The highest basal melt rates (3.9 m yr^{-1}) were observed close to a grounded feature near the ice shelf front. Daily time-varying measurements reveal a seasonal melt signal 4 km from the ice shelf front, at an ice draft of 130 m, where the highest daily basal melt rates occurred in summer (up to 5.6 m yr^{-1}). ~~This~~In comparison with wind, air temperatures, and sea-ice cover from reanalysis and satellite data the seasonality in basal melt rates indicates that summer-warmed ocean surface water was pushed by

wind beneath the ice shelf front. We observed a different melt regime 35 km into the ice-shelf cavity, at an ice draft of 280 m, with considerably lower basal melt rates (annual average of 0.4 m yr^{-1}) and no seasonality. We conclude that warm deep ocean water at present has limited effect on the basal melting of Nivlisen. On the other hand, a warming in surface waters, as a result of diminishing sea-ice cover has the potential to increase basal melting near the ice-shelf front. ~~Many ice shelves like Nivlisen are stabilized by pinning points at their ice fronts and these areas may be vulnerable to future change.~~Continuous in situ monitoring of Antarctic ice shelves is needed to understand the complex mechanisms involved in ice shelf–ocean interactions.

1 Introduction

The Antarctic contribution to global sea-level rise has increased by a factor of five in the past two decades (The IMBIE Team, 2018). ~~This rapid increase in the overall mass deficit is mostly caused by several retreating and thinning glaciers in West Antarctica that lost buttressing forces from their shrinking ice shelves (De Angelis and Skvarca, 2003; Joughin et al., 2014; Rignot et al., 2014).~~ Over 80 % of the grounded ice in Antarctica drains out into floating ice shelves (Dupont and Alley, 2005). The thinning rates of these ice shelves vary widely around the continent (Paolo et al., 2015). The mass balance of an ice shelf is the sum of the ice gain and loss; ice gain comprises the advective input ~~of grounded~~from ice ~~upstream,~~across the grounding zone (where ice detaches from the bed and becomes afloat), snow accumulation, and marine ice accretion~~, and ice~~. Ice loss encompasses surface melting and sublimation, basal melting from the ocean underneath the floating ice shelf, and iceberg calving at the ice front (Bamber et al., 2018). A negative mass balance can affect ice-shelf stability: where ~~the~~a net mass loss reduces back ~~stress~~stresses on grounded ice upstream~~ of the ice shelf~~, leading ~~them~~the tributaries to flow faster (Reese et al., 2018). Understanding controls on the mass balance of ice shelves around Antarctica is therefore the key to ~~gaining~~gain a better understanding of the continent's present and future contribution to global sea-level rise.

Iceberg calving occurs irregularly in time and can have dramatic effects on ice shelf mass balance when it occurs (Hogg and Gudmundsson, 2017). At present, ~~however, basal melting is~~ iceberg calving comprises approximately half of the ~~largest~~ mass~~-~~ loss ~~process for~~from the

Antarctic ~~ice shelves~~ Ice Sheet, where the other half comes from basal melting (Depoorter et al., 2013; Rignot et al., 2013). ~~Melting of ice shelves by the ocean~~Basal melting is not uniform and depends on the ocean properties in the vicinity of the ice shelf, the topography of both the ocean bed, and the ice-shelf base. Jacobs et al. (1992) described ~~three~~how different ~~modes of melting:~~ water masses can melt the ice shelf from below:

In mode 1, ocean water with temperatures at the surface freezing point provides heat for ~~basal~~ melting of deeper parts of the ice base, because the pressure-melting point of the ice is decreased to lower temperatures at depth. ~~Since these cold shelf waters provide a limited source of ocean heat (Darelius~~Basal melting at the deep grounding zones can be high and ~~Sallée, 2017), average melt rates are~~ often ~~low for the largest ice shelves~~occur at basal channels (e.g., ~~0.3~~22 m yr^{-1} for ~~Ronne~~Ross Ice Shelf~~ with; Rignot~~; Marsh et al., ~~2013). In addition~~2016); however, substantial marine~~-~~-ice accretion ~~occurs~~reduces the net melting below these large ice shelves when the rising melt plume from the grounding zone super-cools and refreezes on the ice-shelf base at shallower depths (Joughin and Vaughan, 2004). Since these cold shelf waters provide a limited source of ocean heat (Darelius and Sallée, 2017), average basal melt rates are often low for the largest ice shelves (e.g., 0.3 m yr^{-1} for Ronne Ice Shelf; Rignot et al., 2013).

In mode 2, ice shelves melt from the presence of warm circumpolar deep water intrusion (Jacobs et al., 1992). The rapid retreat and high thinning rates of glaciers in ~~the Amundsen Sea sector of West~~ Antarctica ~~are thought~~have been attributed to ~~be driven by an increased~~the presence of warm circumpolar deep water below ~~the~~ ice shelves in the Amundsen Sea sector of West Antarctica (Pritchard et al., 2012; Rignot et al., 2013~~), referred to as melt mode 2 in Jacobs et al. (1992).~~). Circumpolar deep water surrounds the Antarctic continent, flowing clockwise with the Antarctic Circumpolar Current and is abundant near the continental shelf of West Antarctica. Circumpolar deep water accesses the deep bases of ice shelves directly through cross-continental submarine troughs, causing ~~high~~the higher basal melt rates; for example Rignot et al. (2013) found Pine Island Ice Shelf to have an average melt rate of 16 m yr^{-1}. In East Antarctica, basal melting has been linked to circumpolar deep water intrusion only at ~~Tottem~~Totten Ice Shelf, where annual basal melt rates reached ~11 m yr^{-1} (Rignot et al., 2013; Rintoul et al., 2016). Farther west, in the Weddell Sea sector a cooler modified version of circumpolar deep water is advected along the coast (Dong et al., 2016; Ryan et al., 2016).

~~Ice~~ In mode 3, ice shelves can ~~also~~ melt at shallow depths in the vicinity of their ice fronts when summer-warmed ~~Antarctic~~ surface water is pushed by wind and tides under ice shelves (Jenkins and Doake, 1991; Makinson and Nicholls, 1999; Sverdrup, 1954; Zhou et al., 2014). ~~Jacobs et al. (1992) refer to this as melt mode 3.~~ Antarctic surface water has ~~only recently~~ been observed ~~at~~under the Ross Ice Shelf in West Antarctica (Malyarenko et al., 2019; Stern et al., 2013; Stewart et al., 2019) and at Fimbulisen in East Antarctica (Hattermann et al., 2012), suggesting it may be ~~an~~a more important process in basal melting~~.~~ than previously thought. Spatial patterns and relative magnitudes of all these three modes of basal melting

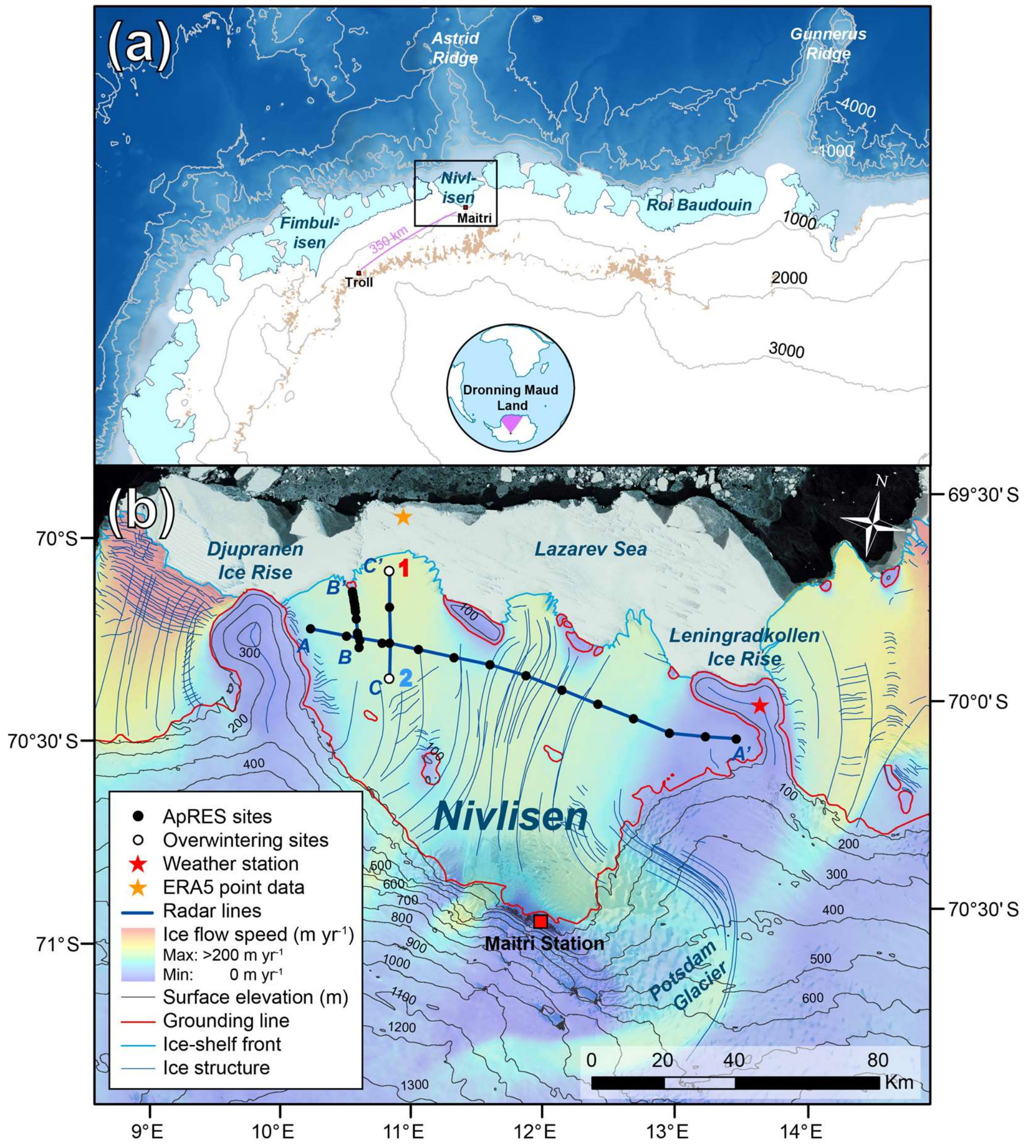

Figure 1. Study area: **(a)** Dronning Maud Land coast, with research stations, ice shelves (light blue), and elevation contours with bathymetric features (Arndt et al., 2013). **(b)** Nivlisen ice shelf with surrounding areas. Study sites, where ApRES and stakes for ice velocity and surface mass balance were located, ApRES overwintering sites (no. 1 called "seaward" and no. 2 called "landward"), and low-frequency radar profiles (A, B, and C). Satellite derived ice speed (Rignot et al., 2011), surface elevation (m a.s.l.; Howat et al., 2019), grounding line, ice-shelf front (Mouginot et al., 2017), and ice structure (Goel et al., in review) are also shown. Background image is Landsat image mosaic with sea ice in front of the ice shelf (Bindschadler et al., 2008). Grid coordinate system is WGS-84.

remain largely unknown. Numerical modelling, however, indicates that the response of basal melting in the future strongly depends on the surface air warming (Kusahara and Hasumi, 2013). Future basal melting in Antarctica will therefore reflect the integrated response to ~~remotely~~ changes in ~~sub-surface~~ circumpolar deep water temperatures and ~~the~~ coastal processes that control its access ~~to~~onto the continental shelf (Thompson et al., 2018~~) and the local upper ocean heat supply.~~). The detailed interplay of these processes today and in a future climate are still a major source of uncertainty when evaluating the response of the Antarctic Ice Sheet to climate change (Adusumilli et al., 2018).

In this study, we measured basal melting at Nivlisen (70° S, 12° E~~),~~) in central Dronning Maud Land, East Antarctica, using autonomous phase-sensitive radio-echo sounders (ApRES; Fig. 1). Phase-sensitive radars ~~uses~~use a technique where the phase of individual internal ice reflectors is tracked, yielding time series of ice thickness change at high~~-resolution~~ accuracy (~1 mm) ~~over~~and short time intervals (Corr et al., 2002; Nicholls et al., 2015~~) and have~~). This technique has been used to measure basal and englacial properties of ice at several locations around Antarctica (e.g., Davis et al., 2018; Jenkins et al., 2006; Marsh et al., 2016; Stewart et al., 2019~~),~~) and~~ recently also~~ in Greenland (Vaňková et al., 2018). Our objective is to study the spatial and temporal variations of basal melting and to ~~explain them~~interpret the results using: (1) radar profiles of ice thickness, (2) in situ measured and satellite-derived or modelled ice flow speed and surface mass balance, and (3) atmospheric forcing from reanalysis data, sea-ice ~~distributions~~distribution, and ocean tides. The data imply that different ~~melt~~ modes ~~were~~of basal melting are present at Nivlisen. Our in situ measured data of basal melting ~~complements~~complement satellite-derived maps of spatially-smoothed time-averaged basal melt rates, and will be a valuable data source~~ of data~~ for validation of ice shelf and ocean models.

2 Study area

~~In the following section, we summarize the geographical, glaciological, and oceanographic settings of the study area.~~ Dronning Maud Land covers a large area of East Antarctica, and its 2000~~-~~ km-long coast is characterized by extensive ice shelves interspersed with numerous ice rises and ~~ice-sheet promontories~~rumples (Fig. 1a). Ice rises are locations where ice-shelf flow is diverted around the grounded ice and are miniature ice caps with their own flow fields from the summit (Matsuoka et al., 2015). Ice rumples are smaller features that impose a disturbance on the ice-shelf flow, causing the ice to thicken upstream with extensive crevassing. Individual ice shelves are relatively small, but extend close to, or even beyond, the continental-shelf break (Heywood et al., 1998). ~~Satellite-derived ice-shelf averaged net basal~~Basal melt rates from satellite data in Dronning Maud Land vary from near zero to 7 m yr^{-1} (2003 to 2008; Rignot et al., 2013). The interior of this region is partly separated by high mountains, causing steep ice surface slopes from the continental plateau towards the coastal areas (Howat et al., 2019). ~~Nivlisen is located in central Dronning Maud Land, 400 km east of Fimbulisen (Fig. 1a), the largest ice shelf in the area. 100 km south of Nivlisen lies the Wohlthat Massif, with a maximum elevation of ~3000 m above sea level (a.s.l.). Between the mountain massif and the ice shelf lies the Schirmacher Oasis, an ice-free area with a maximum elevation of ~250 m a.s.l., with numerous lakes and ponds.~~ The drainage basin of Nivlisen (27 700 km^2), including the grounded ice that drains to the ice shelf, has an ~~ice volume equivalent to 8 cm~~estimated potential of raising global sea- level ~~rise~~by 8 cm (Rignot et al., 2019).

Nivlisen has an areal extent of ~7300 km^2 and forms a closed embayment between two larger promontory-type ice rises, Djupranen and Leningradkollen (Fig. 1b). ~~Ice rises are locations where ice-shelf flow is diverted around the grounded ice and are miniature ice caps with their own flow fields from the summit (Matsuoka et al., 2015). Ice rumples are smaller features that impose a disturbance on the ice shelf flow, causing the ice to thicken upstream with extensive crevassing in the grounding zone.~~ Such grounded features are known to play vital roles in ice-shelf and ice-sheet dynamics over various timescales. For example, un-grounding of an ice rumple within the ice shelves of Pine Island and Thwaites Glacier is thought to be a major cause of the ongoing rapid retreat and thinning (Favier et al., 2012; Gladstone et al., 2012; Jenkins et al., 2010). Bawden Ice Rise near the edge of the Larsen C Ice Shelf helps maintain ~~the shelf~~its stability, despite the collapse of neighbouring Larsen A and B ice shelves (Borstad et al., 2013; Holland et al., 2015). Nivlisen is grounded at a series of smaller ice rises and rumples near the present ice front, as well as at a few ice rumples in the middle of the ice shelf (Moholdt and Matsuoka, 2015). The bathymetry under the ice shelf is unknown.

The average ice shelf flow speed is 80 m yr^{-1} (Rignot et al., 2011). Potsdam Glacier drains into Nivlisen from the southeast, with an average ice thickness of ~1000 m (Fretwell et al., 2013) and ice flow speed of ~50 m yr^{-1} (Anschütz et al., 2007; Rignot et al., 2011). The satellite-derived estimate of the grounding-line flux for Nivlisen was 3.9 ± 0.8 Gt yr^{-1} (2007–2008; Rignot et al., 2013). Elevated topography of the ice rises causes highly-variable local climate and surface mass balance gradients (Lenaerts et al., 2014). In addition, Nivlisen has large surface mass balance transitions from being positive in the firn area near the ice front to being negative in the blue-ice area near the grounding zone, with increased wind erosion, evaporation, and sublimation ~~due~~owing to katabatic winds (Horwath et al., 2006). Near the grounding zone, summer surface melting is sufficient to form supraglacial lakes and streams that may occasionally drain through the ice shelf (Kingslake et al., 2015), making Nivlisen potentially sensitive to hydrofracturing (Lenaerts et al., 2017). Rignot et al. (2013) estimated the surface mass balance to be 1.8 ± 0.3 Gt yr^{-1} (average 1979–2010) and the average calving flux to be 1.3 ± 0.4 Gt yr^{-1} (2007–2008). ~~Together~~These numbers together with the grounding-line flux mentioned earlier and a slightly positive net mass balance of 0.6 Gt yr^{-1} (2003–2008) results in a residual net basal melt of 3.9 Gt yr^{-1}, or an average basal melt rate of 0.5 ± 0.2 m yr^{-1} (Rignot et al., 2013). Thus, basal melting comprises ~75 % of the total ~~mass losses~~outgoing flux, with the ~~remaining~~residual ~25 % ~~coming from~~attributed to iceberg calving.

The continental shelf extends ~100 km north of Nivlisen into the Lazarev Sea, and is roughly 500 m deep (Arndt et al., 2013; Fig. 1a). Carbon dating of laminated sediments on several locations near the ice shelf suggests that the ~~continental shelf was deglaciated~~ice front retreated to its present position by ~11- kyr ago (Gingele et al., 1997). ~~At the eastern border~~North of ~~Lazarev Sea~~Nivlisen lies Astrid Ridge ~~(~12° E~~(Fig. 1a), an undersea bathymetric feature extending from the Antarctic margin northward to ~65° S. Farther east lies Gunnerus Ridge ~~(~33° E~~(Fig. 1a), where circumpolar deep water is entrained~~, which is~~ into the Antarctic slope current. The circumpolar deep water is then cooled and modified to become warm deep water (Dong et al., 2016; Ryan et al., 2016~~). Warm deep water~~) and flows westward along the continental slope ~~and is~~to finally become entrained into the Weddell Gyre. The ice-shelf cavities in this region are separated from warm deep water by the Antarctic slope front, which is a pronounced transition zone over the narrow continental shelf between eastern shelf water and warm deep water. The slope front is mainly attributed to coastal downwelling caused by the prevailing easterly winds (Sverdrup, 1954; Thompson et al., 2018). The coastal dynamics that set the warm deep water depth along the continental-shelf break involves the balance between wind-driven Ekman overturning and counteracting eddy fluxes (Nøst et al., 2011; Thompson et al., 2014). These processes respond to changes in wind and buoyancy fluxes (Hattermann et al., 2014; Stewart and Thompson, 2016), including self-amplifying feedbacks of increased fresh water input from increased basal melting (Hattermann, 2018).

The Southern Ocean, including the Weddell Sea, has warmed over recent decades (Gille, 2002; Schmidtko et al., 2014) with the changes driven primarily by anthropogenic climate warming (Swart et al., 2018). Sea-ice cover has increased slightly since 1979 around Antarctica in general (De Santis et al., 2017), however extreme changes have occurred in recent years with record maxima three years in a row (2012 to 2014), followed by record ~~summertime minimum in~~minima 2016 and 2017 (Shepherd et al., 2018; Stuecker et al., 2017; Turner et al., 2015). Sea-ice fluctuations are strongly correlated with the dominant ~~modes of~~trends in Southern Hemisphere climate variability (Kwok et al., 2016; Kwok and Comiso, 2002), although further studies are needed to understand the drivers behind these fluctuations (Turner 2017). An increase in the seasonality of the easterly winds has been observed (Hazel and Stewart, 2019) and this may affect the formation and export of sea ice and the transport of surface waters and warm deep water to the continental shelf. All these pan-Antarctic observations may affect ocean water flow and ~~then~~consequent ice-shelf thinning in Dronning Maud Land~~, which remain~~ and remains largely unknown.

3 Data and Methods

We conducted three field campaigns on Nivlisen and adjacent ice rises during the Antarctic austral summers, from mid-November until end of December, 2016 to 2018, with logistic support from the Indian Maitri ~~Station~~ and Norwegian Troll Station (Fig. 1a). ~~We~~In December 2016, we installed stakes for measurement of ice velocity and surface mass balance at 29 locations on Nivlisen and measured ~~basal melting under Nivlisen using two~~the ice thickness with an ApRES ~~systems~~system (200–400 MHz), developed by the British Antarctic Survey (British Antarctic Survey, 2018; Nicholls et al., 2015~~). Below, we describe the methods used to collect the ApRES data and process them to derive basal melt rates (Sect. 3.1). We also studied the ice-shelf thickness and basal structure with a low-frequency (5 MHz) radio-echo sounder (Sect. 3.2). Finally, the annual ice flow speed and surface mass balance were measured at stake locations along three profiles on the ice shelf (Sect. 3.3).~~

~~3.1 Autonomous phase-sensitive radar~~

~~In December 2016, we installed stakes for measurement of ice speed and surface mass balance at 29 locations on Nivlisen and measured the ice thickness using an ApRES system (~~; Fig. 1b): (A) 13 stakes were placed across the ice ~~shelf~~flow at a spacing of 10 km (profile A), (2) 10 stakes were placed along the ice flow towards a grounded feature near the ice front with a spacing of 1 to 4 km (profile B), and (3) Four stakes were placed along the ice flow ~~out on an~~towards the ice ~~tongue~~front at a spacing of 10 km (profile C). We also measured the ice-shelf thickness and basal structure with a low-frequency (5 MHz) radio-echo sounder along these three profiles. After the initial measurements, we installed similar ApRES systems at two locations for hourly measurements of basal melting and strain rates over the winter, each powered by a 12 V 114 Ah battery (Fig. 1b): (1) 4 km from the ice-shelf front, called the “seaward site” hereafter, and (2) 35 km from the ice shelf front, called the “landward site”. In December 2017 and 2018, we revisited and re-measured all ~~stake~~ApRES sites to get ~~annual~~ averaged annual values of basal melting and strain rates and retrieved the time-series data from the two overwintering stations. Extensive crevassing prevented the three sites closest to the ice rumple (profile B, Fig. 1b) from being revisited in 2018.

3.1 Autonomous phase-sensitive radio echo sounder

ApRES uses the frequency-modulated continuous wave (FMCW) technique (Rahman, 2016). The instrument transmits a signal sweeping from 200–400 MHz over a period of 1 s to form a chirp (Nicholls et al., 2015). The system has a low-power consumption, with a power to the transmitter antenna of 100 mW. The averaged signal was amplified and de-ramped, a process where the received signal is mixed with a replica of the transmitted signal to extract differences in frequencies. The de-ramped signal was then filtered to amplify the higher frequencies preferentially, which enhanced weaker signals from more distant reflectors. Each sample consisted of 100 chirps, collected over a period of a few minutes. The data were digitized and stored on secure digital cards for further processing.

We processed the data following Brennan et al~~.~~., (2014) and Nicholls et al. (2015~~)~~ ~~(Supplements Fig. S1).~~). The data were Fourier transformed to give a complex signal amplitude as a function of delay time~~,~~ (or depth~~,~~) assuming a constant propagation velocity of 168 m μs^{-1}. An amplitude cross correlation between the two returns, for a depth range within the firn layer (typically from 40 to 70 m~~)~~), provided a vertical shift~~ that~~ that approximately accounted for snow accumulation between the visits. The displacement of the reflectors between the two visits were then plotted as a function of depth~~.~~ (Supplements Fig. S1a). To give the necessary depth resolution, the phase of the signals was used to calculate the displacements by cross-correlating 4 m segments of the first profile with the complex conjugate of the corresponding segment of the second. Under the assumption of a constant vertical strain rate between the bottom of the firn layer and just above the ice base, we fit a straight line to the layer displacements. The~~ effect of the~~ correction for snow accumulation between the two visits~~, both~~ included the coarse correction mentioned above and the precise correction inherent in the phase processing~~, and~~. This effect, together with the effect of the non-linear (with depth) displacements due to firn compaction, ~~are both~~were contained within the intercept at the vertical axis. Thus the basal melt ~~is~~was given by the deviation of the displacement of the basal reflection from the straight line fit (Supplements Fig. ~~S1~~S1b). The error in the calculated strain was estimated using the quality of fit of the linear regression. The uncertainty in the melt rate was obtained by combining the uncertainty in the strain rate with the uncertainty in the change in the range to the basal reflector, deduced from the signal-to-noise ratios of the two basal reflections.

To calculate the hourly melt rate time-series ~~data from~~for the two overwintering sites (Fig. 1b), we tracked the basal ~~returns~~reflector using phase-coherent processing~~, allowing~~. This allowed us to determine the speed of motion of the ice base with respect to the antenna, which we hereafter ~~is called~~call the thinning rate. To remove the component of ice-column vertical strain rate caused by tidal variations, we filtered the basal vertical speeds with a 36 h low-pass filter. We then removed an annual average vertical strain rate from the filtered basal motion, resulting in net basal melt rates. We assumed that, at periods longer than 36 hours, the variability in strain rate is small compared with the variability in basal melt rate and varies on a much longer timescale than those of interest here. .

3.2 Low-frequency radar profiling

In December 2016, weWe collected ~180 km of continuous radio-echo sounding profiles across the ice flow (profile A) and along the ice flow (profile B and C) ofon Nivlisen to measure ice thickness and englacial and basal structure (profiles A, B, and C; Fig. 1b). We used a common-offset impulse radar system (Dowdeswell and Evans, 2004) based on the radar developed by Matsuoka et al. (2012) and processing steps following Lindbäck et al. (2014). We used half-wavelength dipole antennas with a 5 MHz centre frequency, withusing a Kentech impulse transmitter with an average output power of 35 W. The transmitter and receiver systems were mounted on two sleds and towed behind a snowmobile at a speed of ~10 km h^{-1}. We positioned the tracesmeasurements using data from a code-phase global positioning system (GPS) receiver mounted on the radar receiver box 20 m in front of the common mid-point of the antennas along the travelled trajectory of the snowmobile. We post-corrected the height using the Canadian precise point-processing service (CSRS-PPP; Natural Resources Canada, 2017) from a kinematic carrier-phase dual-frequency GPS receiver mounted on the snowmobile. The radar measurements had an average linetrace spacing of ~5 m.

Several corrections and filters were applied to the radar data: (1) dewow and bandpass filters, to remove unwanted frequency components in the data, (2) depth-variable gain function, and (3) normal move-out correction to correct for antenna separation, including adjusted travel times for the trigger delay. The basal returns were digitized semi-automatically with a cross-correlation picker at the first break of the bed reflection (Irving et al., 2007). We calculated ice thickness from the picked travel times of the bed return using a constant radio-wave velocity of 168 m μs^{-1} for ice. We added a correction term of 2 m to account for the faster propagation in the firn based on the snow density (Sect. 3.3).(Supplements Fig. S1c). The firn has a depth of ~50 m, derived from the ApRES internal reflectors. Ice draft was (Supplements Fig. S1c). To show the depth of the base of the ice shelf in the water column we calculated the ice draft from the ice thickness by subtracting the surface elevation, corrected for local sea level

~~(freeboard~~using an EIGEN-6C4 mean geoid height of 17 m (Förste et al., 2014). We estimated the error in ice thickness by standard analytical error propagation methods (Lapazaran et al., 2016; Taylor, 1996), outlined in Lindbäck et al. (2018). The estimation included the error in the radar acquisition and horizontal positioning error, where the radar acquisition errors comprised errors in radio-wave velocity and two-way travel time. Velocity can vary spatially, depending mainly on density. Errors in two-way travel time were estimated to be the range resolution, which is the accuracy of the measurement of the distance between the antenna and the bed. The average radar system error was estimated to 13.3 ± 1.2 m. The surface and base of the ice shelf is relatively flat, giving very small vertical errors ~~in~~from horizontal positioning (0.1 ± 0.2 m). The total error in ice thickness is presented together with the data in Sect. 4.

3.3 Ice flow and surface mass balance from stakes

~~We measured ice flow and surface mass balance at all 29 ApRES stakes on Nivlisen.~~ Stake height over the surface was measured manually, and stake position was measured ~~statically~~ for 15 minutes using carrier-phase dual-frequency GPS receivers at 1 s logging interval. The stakes were revisited and measured in December 2017 and 2018. We processed the positions statically using CSRS-PPP~~.~~ (Natural Resources Canada, 2017). Snow density was measured at five locations on Nivlisen with an auger drill to a depth of 3 m and varied from 430–450 kg m^{-3}. We used the average snow density of 440 kg m^{-3} and an ice density of 917 kg m^{-3} to calculate the surface mass balance in ice equivalent. Ice flow ~~speed~~velocity and surface mass balance were compared with estimates from satellite data (Rignot et al., 2011) and regional atmospheric modelling (van de Berg et al., 2006).

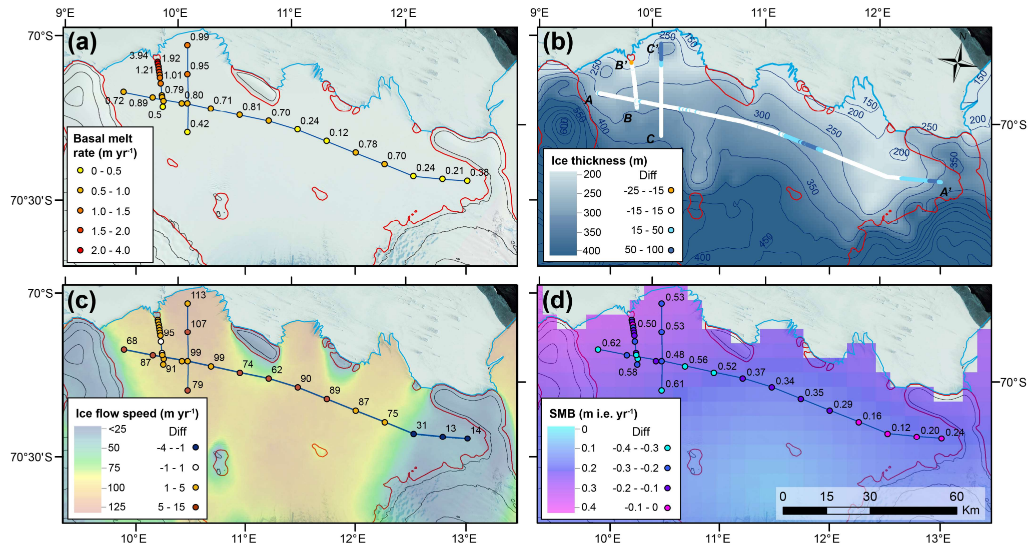

Figure 2. ~~Stake~~Comparison between in situ measured and ~~profile measurements~~satellite derived or modelled values: **(a)** ApRES-derived ~~annual~~ averaged annual basal melt rates ~~for 2017 and hill shade (blue) extracted from the Reference Elevation Model of Antarctica (REMA; Howat et al., 2019).~~. See Supplements Fig. S2 for ~~annual~~ averaged annual basal melt rates for 2018, which is on average within ±10 % from the 2017 values. **(b)** Ice thickness from ~~low-frequency radar profiles (point values) and from~~ Bedmap2 product (grid and contour lines; Fretwell et al., 2013~~).~~) and difference to low-frequency radar profiles (satellite derived minus measured in point colour). **(c)** Ice flow speed from stakes (point numbers) and gridded satellite values (Rignot et al., 2011). Difference (satellite derived minus measured) are shown in point colour. **(d)** Surface mass balance (SMB) from stakes (point numbers) and gridded modelled values (~~Le Brocq et al., 2010). Contour~~van de Berg et al., 2006). Difference (modelled minus measured) are shown in point colour. Background image and contour lines ~~and background images~~ are the same as in Fig. 1.

4 Results

In 2017, ~~annual~~ averaged annual basal melt rates, at 29 ~~stake locations~~ ApRES sites on Nivlisen (Fig. 1b~~)~~), ranged from 0.12 ± 0.06 to 3.94 ± 0.04 m yr^{-1} (Fig. 2a and Fig. 3), with a median value of 0.80 m yr^{-1}. The highest ~~annual~~ averaged annual basal melt rates were observed ~~close to~~ just upstream of an ice rumple at the ice front ~~and the~~. The lowest melt rates were observed in the central and eastern parts of the ice shelf. In 2018, ~~annual~~ averaged annual basal melt rates at 26 ~~locations~~sites, ranged from 0.13 ± 0.06 to 1.48 ± 0.01 m yr^{-1}~~, excluding three sites closest to the ice rumple, with high melt rates in 2017~~ (Supplements Fig. S2). ~~The~~In 2018, the median melt rate ~~in 2018~~ was 0.72 m yr^{-1}. ~~Melt~~Basal melt rates were slightly lower in the second year at 18 sites and for 8 sites slightly higher. ~~Excluding the~~The measurements in 2018 excluded three sites closest to the ice rumple, which had the highest melt rates in 2017, since we were not able to revisit these sites because of many crevasses in ~~2017, annual basal melt rates between 2017 and 2018 differ by ± 0.1 m yr^{-1}.~~the area. Errors in basal melt rates were on average 0.023 m yr^{-1} in 2017 and 0.025 m yr^{-1} in 2018.

Strain rates ~~were in general low, having~~had a median ~~annual~~ averaged annual value of -4.7×10^{-4} yr^{-1} in 2017 and -4.6×10^{-4} yr^{-1} in 2018. The vertical strain-rate contribution to the average rate of thickness change was on average 22 %. The errors in strain were low, on average 6.2×10^{-5} yr^{-1} in 2017 and 7.1×10^{-5} yr^{-1} in 2018. For most parts of the ice shelf the strain rates were negative, meaning that the ice was thinning by longitudinal stretching, however, close to the ice rumple mentioned earlier (profile B; Fig. 3) we observed a transition from negative to positive strain rates (from -5.4×10^{-4} to 2.2×10^{-2} yr^{-1}), with increasing compressional thickening of the ice towards the ice rumple. Positive strain rates were also observed for five sites 5–10 km upstream of the larger ice rises in the central and in the eastern part of the ice shelf (profile A; Fig. 3), indicating a far-reaching buttressing effect (distance up to ~30 ice thicknesses from the ice rises).

The two overwintering ApRES systems were used to derive time series of basal melt rates. The seaward overwintering site was located 4 km from the ice front and had an ice draft of 130 m, as measured with low-frequency radar. It operated for 14 months (from 11 Dec 2016–4 Feb ~~2017~~2018) before the battery failed. Thirty-six hour low-pass filtered basal melt rates at this site varied from ~0 to 5.6 m yr^{-1}, where the highest melt rates occurred in summer (29 Jan 2017; Fig. 4a). The landward overwintering site was located 35 km from the ice front and had an ice draft of 280 m. The data cover ~~23~~22 months (from 4 Jan 2017–27 Nov 2018), ~~except for~~excluding December 2017 when the instrument was used for measuring annual basal melt rates at other ~~locations~~sites. At this site, 36 h low-pass filtered basal melt rates varied from ~0 to 2.0 m yr^{-1}, where the highest melt rates occurred in winter (12 Jun 2018; Fig. 5a).

Ice thickness, measured with low-frequency radar along profiles A, B, and C (Fig. 1b), varied from 160 to 330 m (Fig. 2b), with a median value of 260 m. We observed the thinnest ice close to the ice front along profile C (Fig. 3) and the thickest ice in the southern-most part of the ice shelf along the same profile. The total error in ice thickness along the profiles, including radar system and positioning errors, varied between 10.6 and 15.7 m. The broad thickness pattern ~~agreed~~agrees with ~~satellite-derived freeboard estimates from~~the gridded ice thickness of Bedmap2 (Fretwell et al., 2013), except close to the ice front in the western part (profile C), where the thickness of Bedmap2 is clearly too high (Fig.

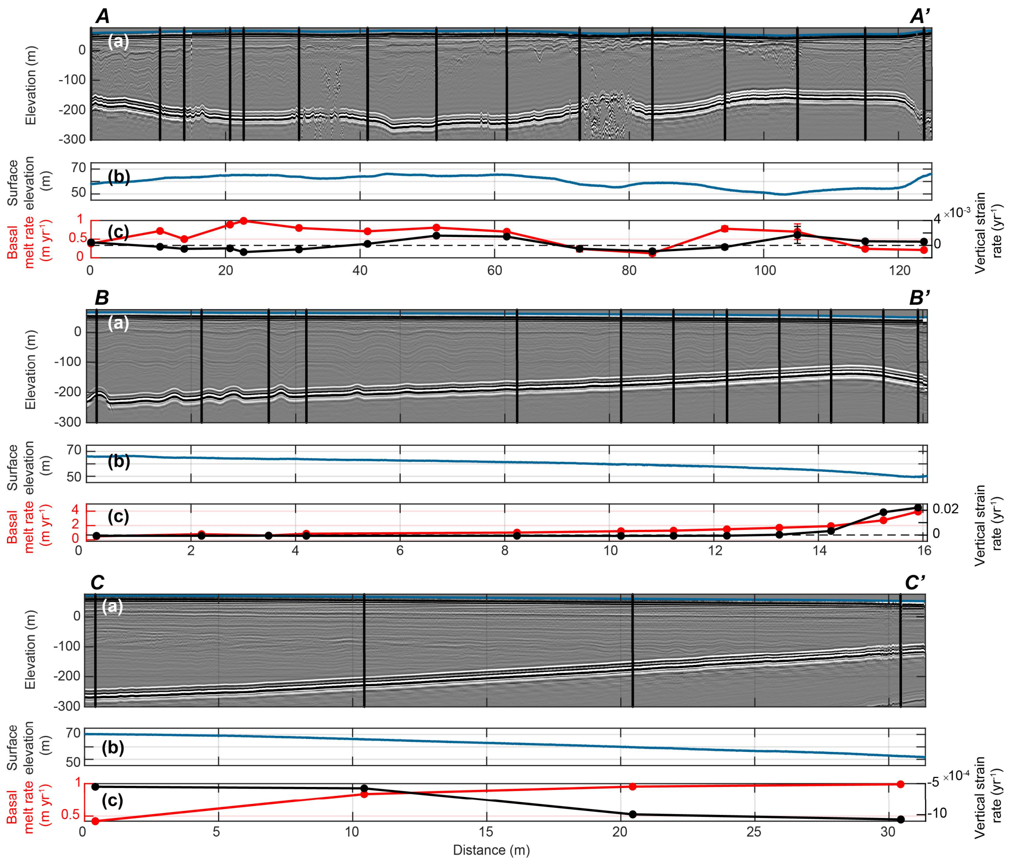

Figure 3. Profiles of low-frequency radar, ice surface elevation, basal melt, and strain (locations in Fig. 1b): A–A' across ice flow from west to east (125 km), B–B' along ice flow from south to north towards an ice rumple (16 km), and C–C' along ice flow from south to north out ~~on an~~towards the ice ~~tongue~~front (32 km). Sub-panels show **(a)** radar profiles with surface elevation (blue line), englacial stratigraphy, and basal elevation (grey tone shading), and locations of ApRES measurements (black vertical lines), **(b)** surface elevation from carrier-phase kinematic GPS measurements, and **(c)** annual basal melt rate (red) and vertical strain rates (black, dashed = 0) for 2017. Note that the x-axis scales vary between the three profiles. ~~Surface elevation is referenced to local sea level (freeboard).~~

~~on the western ice tongue (profile C), where the thickness reported in Bedmap2 is too high (Fig. 2b).~~2b), possibly due to errors in the input data or the interpolation between them. Ice draft varied from 120 to 280 m with a median value of 220 m (Fig. 3). We observed no significant relation between basal melting and ice draft. Several locations with undulating englacial layers, basal channels and crevasses were visible in the radar profiles (Fig. 3). Stake-measured ice flow speeds varied from 13 to 113 m yr^{-1} in 2017, with an average value of 80 m yr^{-1}, agreeing with satellite estimates (Rignot et al., 2011; Fig. 2c). Surface mass balance values varied between 0.12 and 0.62 m i.e. yr^{-1} in 2017 with an average of 0.45 i.e. yr^{-1}, higher than the modelled average estimates of 0.2 m i.e. yr^{-1} (van de Berg et al., 2006), but with the same spatial pattern (Fig. 2d).

5 Discussion

In the following sections, we discuss the spatial ~~(Sect. 5.1)~~ and temporal ~~(Sect. 5.2)~~ variations in basal melting and compare our results with other studies from Antarctica. For each section, we also discuss strengths, limitations, and recommendations for future studies.

5.1 Spatial variations in melting

On Nivlisen, we observed the highest ~~annual~~ averaged annual basal melt rates (3.9 m yr^{-1}) close to a small (4.2 km^2) ice rumple at the ice front (Fig. 2a and Fig. 3). Similar ~~high~~basal melt rates (~4 m yr^{-1}) were inferred from satellite data nearby Bawden Ice Rise in the Antarctic Peninsula (Adusumilli et al., 2018). In modelling experiments, ~~the higher~~locally enhanced basal melt rates ~~arose from the generation of energetic short-length-scale diurnal topographic vorticity waves~~ were caused by strong tidal currents in shallow regions (~~(Mueller et al., 2012). This required a~~ thin water column ~~(shallow bathymetry) under~~thickness) around the ice rise that increased the ice-ocean heat exchange (Mueller et al., 2012). ~~shelf.~~ At Nivlisen, we have no observations of ~~tidal strengths~~ocean currents near the ice rumple, but the bathymetry must be shallow since the ice shelf grounds in this region. Ice shelf thinning could potentially increase the water column ~~depth and have~~thickness, leading to a negative (stabilizing) feedback on the melting~~,~~ by reducing the ~~topographic vorticity waves~~ocean currents (Mueller et al., 2012, 2018; Padman et al., 2018~~), though no clear relationship was found between ice draft and basal melting~~

~~rates in our study.~~). In terms of ice thickness change, the observed thinning from the basal melt is compensated by a positive vertical strain that implies compressional thickening towards the ice rumple (up to 4 m yr^{-1}). Thicker ice towards the ice rumple indicates a buttressing effect on the ice shelf (profile B; Fig. 3). We observed many crevasses in this region that made it, for safety reasons, difficult to revisit the three closest sites during the third field season (Dec 2018). ~~The effects of sustained high melt rates~~Many ice shelves like Nivlisen are stabilized by pinning points at their ice fronts, which may be sensitive areas for future change. The effects of an increased basal melting in the future at the Nivlisen ice rumple are uncertain, and modelling work may indicate whether un-grounding of the ice would potentially lead to substantial loss of buttressing (Borstad et al., 2013).

Estimates of basal melt rates for Dronning Maud Land ice shelves have mainly used satellite techniques, modelling, or limited spatial or temporal coverage of in situ radar observations (Berger et al., 2017; Langley et al., 2014b). Fimbulisen is situated 400 km west of Nivlisen (Fig. 1a) at the outlet of Jutulstraumen, one of the largest ice streams in Dronning Maud Land. Below the deep keel from Jutulstraumen (300–400 m ice draft), time-averaged basal melt rates of several meters per year were observed, whereas at the shallower parts of the ice shelf (200–300 m ice draft), lower melt rates were observed (Langley et al., 2014a). In addition, annual-average basal melt rates were modelled to be near zero for large areas (Hattermann et al., 2014). Hattermann et al. (2014) hypothesized that basal melting (melt mode 1, Sect. 1) occurred at the deepest parts of Fimbulisen (below ice drafts of 400 m). The rising melt plume caused marine accretion at shallower depths closer to the ice front, which together with seasonal ~~mode-3~~ melting~~, resulting~~ from summer-heated surface water (melt mode 3, Sect. 1), resulted in the low net basal melt rates~~, with~~. The seasonal marine~~-~~-ice formation ~~being~~was inferred from an ice shelf cavity mooring (Hattermann et al., 2012). Nivlisen is in comparison relatively thin (Fig. 2b) and we have no melt observations from the thicker ice in the southern areas. Grounding line ice drafts (Fig. 1b), derived from Fretwell et al. (2013) and Mouginot et al. (2017), have an average value of 350 m. The deepest part of the grounding line (630 ± 100 m) is located at the outflow of Potsdam Glacier (Fig 1b), where higher basal melt rates may occur. In addition, Nivlisen has three ice~~-tongues-~~front sections, separated by ice rises and ice rumples, where the ocean can gain access to the inner parts of the ice shelf cavity. At Fimbulisen, Hattermann et al. (2012, 2014) found that a portion of the westward flowing coastal current was diverted under the ice shelf between two ice rises. Similar inflow pathways may also exist beneath the ice~~-tongues~~-front sections of Nivlisen, explaining the variations of basal melt rates along profile A (Fig. 2a). At Fimbulisen, ~~high~~higher basal melt rates (3 m yr^{-1}) were also observed and modelled close to the ice front at shallow depths (< 200 m; Hattermann et al., 2014; Langley et al., 2014b), which is consistent with our results.

In the low-frequency radar profiles, we observed several undulating ice-base features (profile A and B; Fig. 3), where the englacial layers warp downwards, which is likely an indication of basal channels or crevasses. The southernmost measurement in profile B is located at one of these down-warping features, where surface elevation is slightly lowered locally (–0.5 m). Higher basal melt rates were not observed here compared with the surrounding sites, although, higher melt rates typically occur on the flanks of basal channels, rather than at their apex (Berger et al., 2017). The channel may have formed at an upstream ice rumple and been passively advected downstream (Fig. 2a). Basal channels are important features influencing the ice-shelf stability, since they affect ice-shelf cavity circulation and play a role in the exchange of heat and mass between the ocean and ice shelf (Gladish et al., 2012; McGrath et al., 2012; Millgate et al., 2013; Stanton et al., 2013). Basal channels are not restricted to rapidly melting ice shelves and have been observed elsewhere in Dronning Maud Land, at Fimbulisen (Langley et al., 2014a) and Roi Baudouin Ice Shelf (Fig. 1a; Berger et al., 2017). Detailed studies of these features together with basal melting are needed to understand their initiation, evolution, and role in the overall mass balance of ice shelves (Alley et al., 2016).

5.2 Temporal variations in melting

~~Melt~~Basal melt rates at Nivlisen varied on a broad range of timescales (Fig. 4 and 5). At the seaward site, we observed a seasonal signal, where the monthly averaged basal melt rates were two to three times higher in the summer than in winter (Fig. 4a, Supplements Fig. S3). At the landward site, we observed no seasonal pattern, however, some variability on monthly time-scales was present (Fig. 5a, Supplements Fig. S3). We performed a continuous wavelet transform on the time-series data from the two overwintering sites, based on the method and software package provided by Grinsted et al. (2004). The wavelet transform is used to study localized intermittent periodicities, in contrast to more traditional mathematical methods, such as Fourier analysis, which assumes that the underlying process is stationary in time. We used a Morlet wavelet with $\omega_0 = 6$, which provides a good balance between time and frequency localization. The wavelet transform shows the normalized thinning rates at different scales to identify dominant periods of variability in time (Fig. 4b, 5b). The statistical significance was assessed relative to the null hypothesis, modelled by a first order autoregressive process. The wavelet transform has edge artefacts since it is not completely localized in time, as indicated by the cone of influence, masking out low frequency signals at the beginning and end of the time series. ~~-~~The thinning variability at diurnal timescales, and to some extent semi-diurnal timescales, varied at an approximately two-weekly period. This reflects the fortnightly spring-neap tidal cycle at ~~which the strength of the tidal currents varies due to the interference of different constituents, usually M_2 and S_2 in this area (plotted as white dashed lines in Fig. 4b and 5b). Stronger tidal currents increase the heat exchange at the ice-ocean interface and may hence cause more rapid melt. At~~

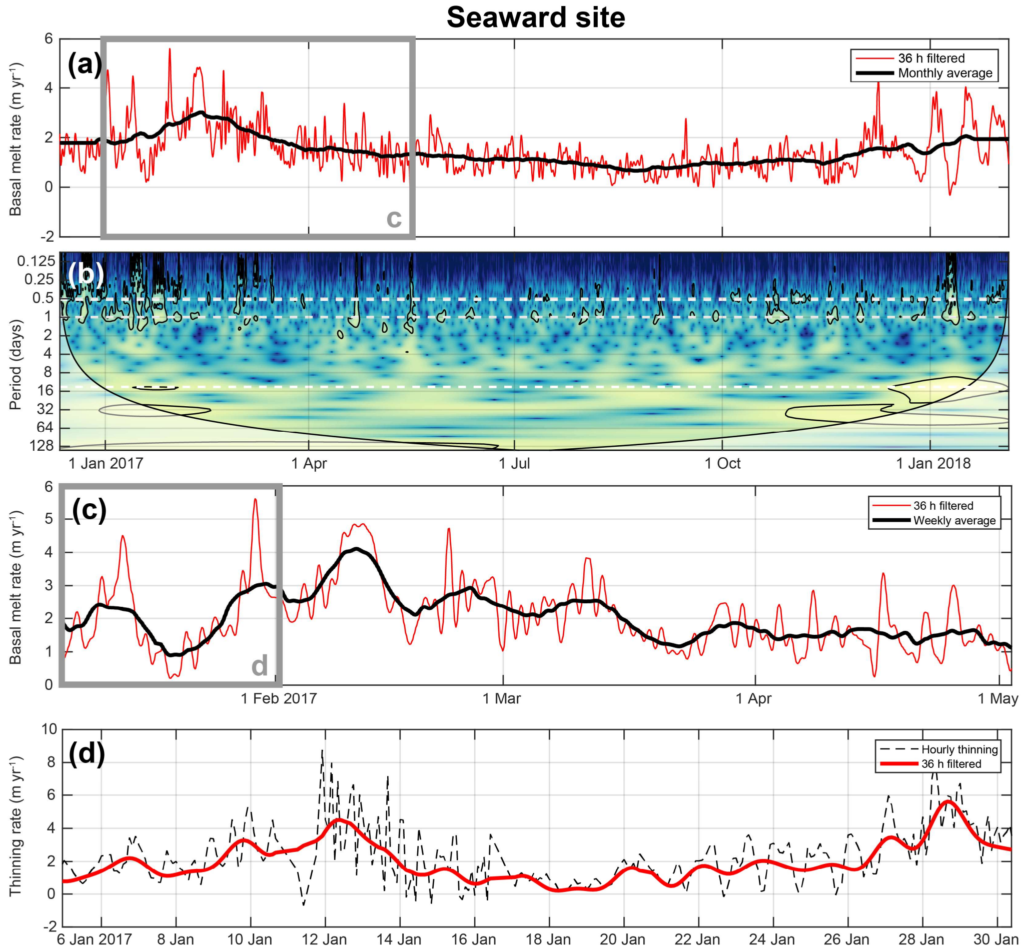

Figure 4. Basal melt and thinning rates for the seaward overwintering site, with variations on time scales of **(a)** months (11 Dec 2016–4 Feb ~~2017~~2018), **(c)** weeks (1 Jan–1 May 2017), and **(d)** days (1–31 Jan 2017). Dashed black line in (d) is the unfiltered raw data with thickness change including strain rates. **(b)** Continuous wavelet transform of the normalized thinning to identify the dominant modes of variability at different time scales. The left axis is the Fourier period. The colour shading represents the thinning associated with fluctuations over the course of the year with a particular time period (yellow = high power, blue = low power). The black contours delimit significant modes of variance at 95 % against red noise. Within the cone of influence, shown as a lighter shade in the right and left lower corners, edge effects ~~become important~~may distort the image. Dashed white lines show the periods of major tidal constituents (0.5 d ≈ K_1, 1 d ≈ M_2/S_2, and 14 d ≈ M_f).

which the strength of the tidal currents varies because of the interference of different constituents, usually M_2 and S_2 in this area (plotted as white dashed lines in Fig. 4b and 5b). Stronger tidal currents increase the heat exchange at the ice-ocean interface and may hence cause

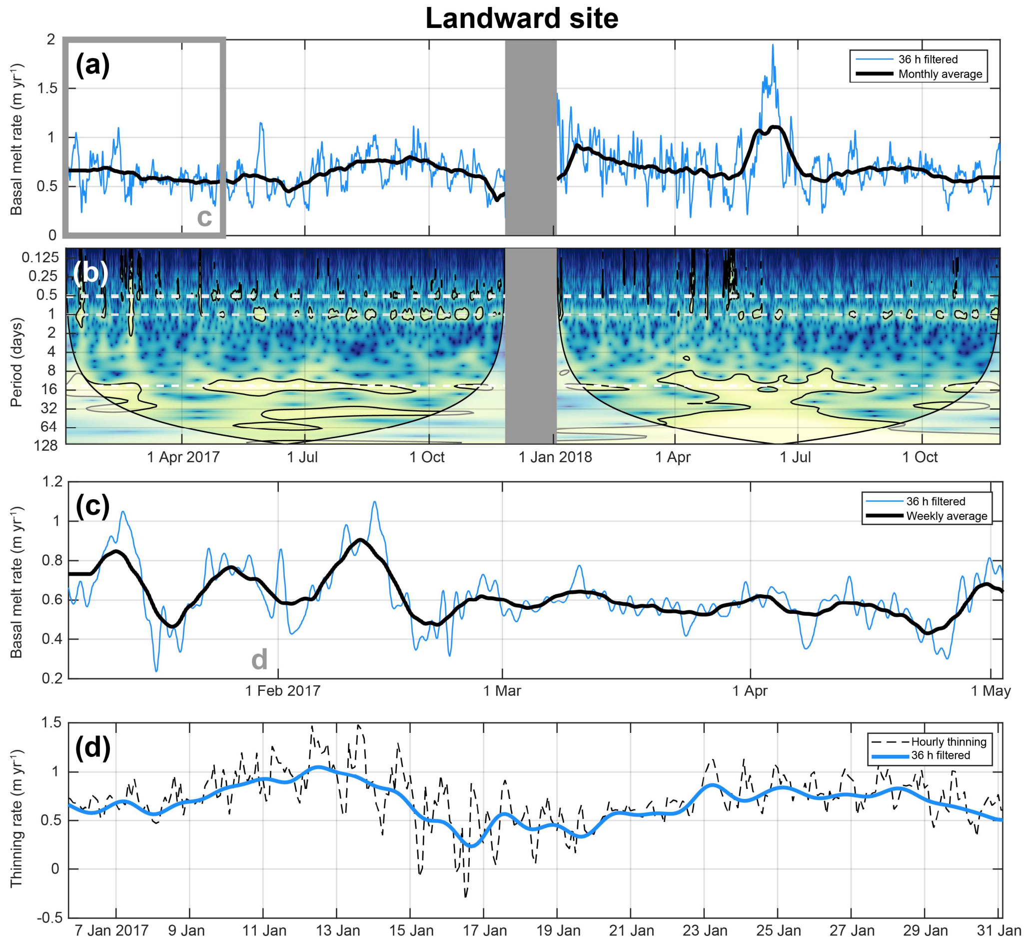

Figure 5. Basal melt and thinning rates for the landward overwintering site, with variations on time scales of **(a)** months (4 Jan 2017–27 Nov 2018), **(c)** weeks (4 Jan–1 May 2017), and **(d)** days (4–31 Jan 2017). **(b)** Continuous wavelet transform of the normalized thinning to identify the dominant modes of variability at different time scales. Grey box masks a time period with no data. See Fig. 4 caption for more information.

more rapid melt. At periods shorter than 36 hours, however, we cannot differentiate the strain signal from the melt signal. We also see some evidence of a slower variability in the data centred on 2–4 days (Fig. 4d and 5d), which may be a result of mesoscale activity passing by the site (eddies or internal waves), which then show up in the melt rate. This is to some extent supported by Fourier analysis of the normalized 36 h filtered basal melt rates, which show peaks in power spectral density at 2–4 days, mostly visible at the seaward site (Supplements Fig. S4).

At the landward site, we observed no increased melting in summer, but we observed one melt peak in winter (12 June 2018; Fig. 5a). The melt event may have been caused by pulses of modified warm deep water reaching the base of the ice shelf as described by Hattermann et al. (2012), but it could also relate to other mesoscale activities within the cavity. In any case, the isolated event and the generally low basal melt rates suggest that warm deep water had limited access to the base of Nivlisen during 2017 and 2018. The observation is consistent with earlier studies, showing that ice shelf cavities in this region are mainly filled with cold and fresh eastern shelf water (Nicholls et al., 2006; Thompson et al., 2018). ~~Along most of the Dronning Maud Land coast, the ice shelf cavities are separated from warm deep water by the Antarctic slope front, which is a pronounced transition zone over the narrow continental shelf between eastern shelf water and warm deep water, mainly attributed to coastal downwelling caused by the prevailing easterly winds (Sverdrup, 1954; Thompson et al., 2018).~~ Many factors control the extent to which warm deep water can access the ice shelf cavities in Dronning Maud Land, such as the stability of the Antarctic slope front, local circulation, and bathymetry~~. The coastal dynamics that set the warm deep water depth along the continental shelf break involves the balance between wind-driven Ekman overturning~~, and ~~counteracting eddy fluxes (Nøst et al., 2011; Thompson et al., 2014). These processes respond~~this has to ~~changes in wind and buoyancy fluxes (Hattermann et al., 2014; Stewart and Thompson, 2016), including self-amplifying feedback of increased fresh water input from increased basal melting (Hattermann, 2018).~~ be studied in more detail.

We studied the coherency between the two overwintering melt sites in a wavelet coherence (Grinsted et al., 2004) for the overlapping time periods in 2017 (Fig. 6). The wavelet coherence analysis finds significant coherence even if the common power is low, and it shows significant confidence levels against red noise backgrounds. Locally phase-locked behaviour can also be revealed; at weekly to monthly periods (7~~ to ~~–30 days) in summer to fall (Jan–Apr 2017) the basal melt rates were in phase, whereas in winter (Apr–Jun) the melting at the seaward site led the increased signal, preceding the melt at the landward site. In late winter (Sept), the phase shifted to the landward site leading the melt. At Fimbulisen, the inflow of summer-warmed

Antarctic surface water was observed at moorings close to the ice shelf front with a clear seasonal signal in water temperatures and salinity (Hattermann et al., 2012). Hattermann et al. (2014) suggested that Antarctic surface water can reside for several months ~~in~~below the ice shelf cavity, after initially being subducted beneath the ice front, potentially affecting basal melting deep inside the cavity. The observed melt rate pattern beneath Nivlisen may be an indication of similar movement of water masses below the ice shelf and further modelling is needed to study these processes, currently being hampered by the lack of knowledge of ~~bottom topography~~bathymetry beneath the ice shelf.

We compared the basal melt rates with atmospheric ERA5 reanalysis data of wind speed, wind direction, ~~sea-ice cover,~~ air ~~pressure, and~~ temperature, and sea-ice cover (Fig. 7) produced by the European Centre for Medium-Range Weather Forecasts (Copernicus Climate Change Service (C3S), 2017) at a grid

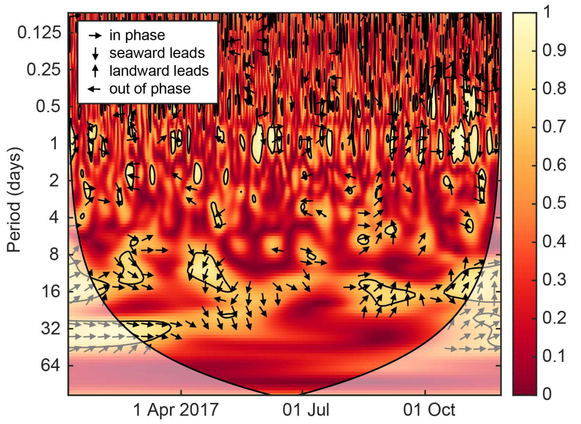

Figure 6. Wavelet coherence between overlapping time periods of the seaward and landward site (4 Jan–27 Nov 2017), showing times where the basal melt rates have common power. The phase relationship is shown as arrows. At longer periods (8–30 days) in summer to fall (Jan–Apr) the signals are in phase, whereas in winter (Apr–Jun) the melt at the seaward site leads the signal. In late winter (Sept) the phase shifts to the landward site leading the signal. Within the cone of influence, shown as a lighter shade, edge effects become important.

point 10 km north of the ice shelf front (Fig. 1b). ERA5 wind speeds at Nivlisen varied on daily timescales, ranging from 0 to 28 m s^{-1}. Winds generally blew from the east (Fig. 7b), corresponding to the pressure gradients imposed by the cyclonic system that dominates the

Weddell Sea. ~~Wind~~As wind forcing can play an important role in downwelling and transportation of summer-warmed Antarctic surface water into the ice-shelf cavity (Zhou et al., 2014). We calculated the coherence between the normalized basal melt rates at the seaward site and wind speeds~~.~~ during time periods when there was open water in front of the ice shelf (grey area in Fig. 7a). The statistical significance level was estimated using Monte Carlo simulation with a Fourier transform method, where a large set of surrogate data set pairs were generated using phase randomization (Schreiber and Schmitz, 2000). ~~In summer, we find~~ We found a significant coherence between basal melt rates and wind speeds (r = 0.~~36~~35, p < 0.~~05; Supplements~~01; Fig. 8).~~S5). Inspecting individual melt peaks in the summer (dashed vertical lines in Fig. 7) show that they coincide with higher wind events, and have a time lag of ~0 to 3 days.~~ We found no such coherence in ~~-~~winter. The variability in winter may be due to the transport mainly dominated by eddies, shed by instabilities in the along-slope current. ~~Sea-ice cover according to ERA5 decreased or was absent (defined as less than 15 %) during~~ We also compared individual melt peaks in the summer ~~and fall (January to March; Fig. 7c), also coinciding~~ with higher ~~melt rates. When~~ wind events (dashed vertical lines in Fig. 7). The melt ~~increased in early summer at the seaward site (Dec 2016 and 2017; Fig 4a), we observed less sea-ice cover close to the ice shelf front, which is the~~peaks have a time ~~when solar radiation may warm the surface waters. Satellite images also show the variability in sea ice (Supplements Fig. S6), with open water east~~lag of ~~the ice tongue in December 2017 that is not resolved in detail in the ERA5 sea-ice cover. The ERA5 air~~~0 to 3 days after a wind event. Air temperatures at 2 m varied mostly on seasonal time scales, with temperatures between 0 and −10° C in summer, when we observe the highest basal melting, and down to −~~24~~28° C in winter (Fig. ~~7d~~7c). The temperature variability in the reanalysis data on shorter timescales agreed with our weather station on Leningradkollen ice rise (190 m a.s.l.), however, the seasonal temperature signal had a lower amplitude than at the weather station, which measured temperatures down to −38° C.

When air temperatures were high and basal melt rates increased in early summer at the seaward site (Dec 2016 and 2017), we observed open water close to Nivlisen, which is the time when solar radiation may warm the surface waters (Fig. 7). Sea ice is widespread in front of the ice shelf during winter and then breaks up during summer typically starting from the west and progressing to the more sheltered eastern side (Supplements Fig. S5). The general pattern of summer retreat is interrupted by irregular periods of some sea ice re-growth (e.g. early February 2017 and 2018; Fig. S5). Similar seasonally higher basal melt rates (up to ~5 m yr^{-1}) were observed at Ross Ice Shelf in West Antarctica, where solar-heated surface water in a polynya near the ice front was linked to the higher melt rates; however, they did not find any link to downwelling-favourable winds, but rather density gradients caused by seasonal brine release in the polynya (Stewart et al., 2019).

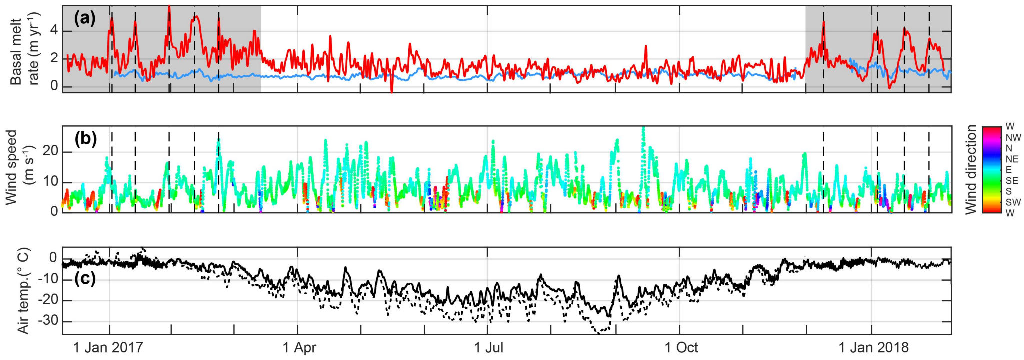

Figure 7. ~~Melt peaks~~Basal melt rates compared with atmospheric forcing and sea~~-~~-ice cover: **(a)** Thirty-six hour low-pass filtered basal melt rates at seaward site (red) and landward site (blue). Shaded grey area represents the time period in satellite data when there is open water in front of the ice shelf (Supplements Fig. S6). ERA5 reanalysis surface data of **(b)** wind speed and direction~~,~~ and **(c)** 2 m air temperature, where dashed black line is data from a nearby weather station (Fig. 1b~~), and **(d)** sea-ice cover, where the dotted line is 15 % (definition of no sea ice). Periods with pronounced basal melting are indicated with vertical~~). Vertical dashed lines ~~for easier comparison~~show where time lags were calculated between basal melt and wind peaks.

~~In summary, the observed higher~~

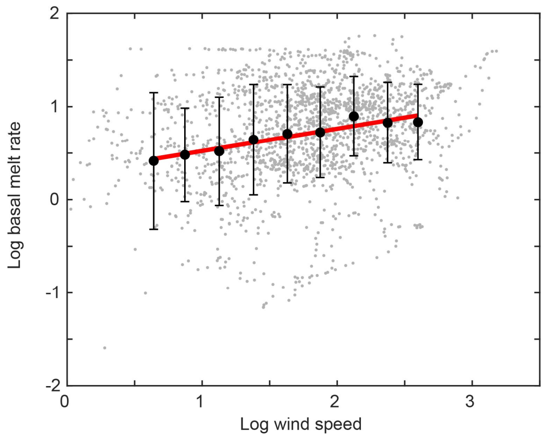

Figure 8. Scatter plot with the normalized basal melt rates ~~during summer and fall correlate with higher~~ at the seaward site and wind speeds~~,~~ for the time period when there ~~is less sea-ice cover and higher air temperatures.~~was open water in front of the ice shelf (grey area in Fig. 7a). Black points show average basal melt rate calculated for each wind speed bin of 0.25 intervals. The red line shows the linear regression.

In summary, the basal melt rates varied on seasonal, monthly, and daily timescales related to the tidal cycles and mesoscale activities in the ice-shelf cavity. We hypothesize that summer-warmed Antarctic surface water was pushed by wind under the ~~ice shelf at the front.~~front of Nivlisen ice shelf. Reduced sea-ice cover and higher wind speeds may increase melting from surface waters, while weaker winds and/or changes in the surface buoyancy forcing may increase exposure of the sub ice-shelf cavities to warm deep water. Surface winds are projected to intensify over the next century with increased greenhouse gas emissions (Greene et al., 2017) and extreme changes in sea-ice extent have occurred in recent years (Shepherd et al., 2018). Warming of the surface water is projected to increase ice-shelf melting along Dronning Maud Land in future climate scenarios (Kusahara and Hasumi, 2013) and recent studies suggest that non-linear feedbacks may facilitate an irreversible transition into a state of ~~high~~higher melting in the Weddell Sea (Hattermann, 2018; Hellmer et al., 2017). ~~Surface winds are projected~~Increases in basal melting will tend to ~~intensify over~~thin the ~~next century with increased greenhouse gas emissions (Greene et al., 2017) and extreme changes in sea-ice extent have occurred in recent years (Shepherd et al., 2018). Natural variability in the atmosphere and oceans remains poorly understood (Turner et al., 2016) and the declining extent of~~ ice shelves ~~around Antarctica has been ascribed~~ and reduce the buttressing on the inland ice sheet. It remains to ~~a~~

~~complex set of processes linking~~ be understood to what extent, increased summer-warmth driven melting, intensified in the ~~atmosphere, ocean, and sea~~vicinity of pinning points may affect the ice ~~(Adusumilli et al., 2018; Greene et al., 2017).~~flow dynamics and ice-shelf stability.

6 Conclusions

We present a two year record of basal melting at Nivlisen~~,~~ in Dronning Maud Land, East Antarctica, at high spatial and temporal resolution using in situ phase-sensitive radar measurements. ~~Annual averaged~~Averaged annual basal melt rates are in general moderate~~,~~ (0.8 m yr^{-1}), but relatively high melt rates were observed close to a grounded feature near the ice shelf front. ~~Daily~~Hourly measurements also reveal a seasonal melt pattern close to the ice shelf front, where the highest basal melt rates occurred in summer~~.~~ (5.6 m yr^{-1}). Comparing the seasonality in basal melting with forcing from atmospheric reanalysis data, we found that the variability in the basal melt is likely caused by summer-warmed surface water pushed by the wind into the ice-shelf cavity. Farther into the ice-shelf cavity, we observe a different melt regime, with significantly lower basal melt rates and a clearer tidal signal. We conclude that warm deep ocean water has a limited effect on the basal melting of Nivlisen, likely because the present configuration of the Antarctic slope front, which separates the deeper water from the continent, protects the ice shelf from those warmer water masses.

Our study highlights that, although many of the ice shelves ~~of~~in East Antarctica have generally low basal melt rates, their seaward ~~portions remain susceptible to~~sections have temporally higher basal melt rates ~~of melting~~ due to the influence of summer-warmed surface waters. ~~Reduced sea-ice cover and higher wind speeds may increase leading mode-3 melting, while weaker winds and/or changes in the surface buoyancy forcing may increase exposure of the sub ice-shelf cavities to warm deep water and therefore increase mode-2 melting. Increases in basal melting will tend to thin the ice shelves and reduce the buttressing on the inland ice sheet. Many ice shelves like Nivlisen~~ The frontal areas are stabilized by pinning points ~~at their ice fronts, which may~~and these areas could potentially be sensitive ~~areas for~~to future change~~. It remains to be understood to what extent, increased summer-warmth driven melting, intensified in the vicinity of these pinning points may affect the ice flow dynamics and ice-shelf stability. Our~~

~~study shows~~ if the basal rates would increase. We demonstrate the use of and need for continuous in situ monitoring of Antarctic ice shelves to resolve variability in basal melting that is not captured in satellite data. Long-term, high-resolution time-series data are ~~important~~crucial to understand the complex mechanisms involved in ice shelf–ocean interactions~~, which in turn is important for ice sheet models~~.

Data availability

The compiled data sets of basal melt rates, strain rates, ice ~~speeds~~velocity, surface mass balance, and low-frequency radar profiles ~~will be~~are available at the Norwegian Polar Data Centre (https://data.npolar.no).

Author contribution

KL led the overall data analysis and interpretations~~,~~ and prepared the paper with contributions from all co-authors. KL, GM, and BP collected the ApRES, ice flow speed, and surface mass balance in the field. KWN was responsible for the ApRES system setup. KM was responsible for the low-frequency radar system and collected the data in field. TH contributed to the discussion section. MT and KM were the project leaders.

Competing interests

KM is a member of the editorial board of the journal.

Acknowledgments

This work was part of the MADICE (Mass balance, dynamics, and climate of the central Dronning Maud Land coast, East Antarctica) project, funded by the Research Council of Norway (project 248780) and the Ministry of Earth Sciences, India (project MoES/Indo-Nor/PS-3/2015). ~~Logistic support was provided from Indian Maitri Station and Norwegian Troll Station,~~

~~Antarctica; we~~We would like to thank the NCPOR and NPI logistic heads and personnel who helped us in the field. We would also like to thank Chris Borstad for estimating flowlines to the rumple, Harvey Goodwin for assessing field safety, Vikram Goel for helping collect the data in field, and Robert Graham for providing the ERA5 data. Figures 1 and 2 were prepared using Quantarctica (quantarctica.npolar.no). For the REMA data set we acknowledge the following: DEMs provided by the Byrd Polar and Climate Research Center and the Polar Geospatial Center under NSF-OPP awards 1543501, 1810976, 1542736, 1559691, 1043681, 1541332, 0753663, 1548562, 1238993 and NASA award NNX10AN61G. Computer time provided through a Blue Waters Innovation Initiative. DEMs produced using data from DigitalGlobe, Inc. We thank the two anonymous reviewers and the editor Nanna B. Karlsson for their suggestions and comments.

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