Response Letter

Dear Editor,

We thank the reviewers for their constructive comments. We have considered all suggestions carefully. Please see our responses below. We regret that the previous versions included language issues; the revised manuscript that we are submitting now was proof-read by an English editing service. Overall, we believe that this version meets journal's criteria but we are also willing to revise the manuscript if it is not the case.

In this letter, we refer page and line numbers in the marked manuscript.

Thanks for handling our manuscript.

Vikram Goel, on behalf of coauthors

Review #1

Review of: Glaciological settings and recent mass balance of Blåskimen Island in Dronning Maud Land, Antarctica, Goel and others, tc-2017-61

This paper provides a study of the glacial conditions, largely concerning mass balance, of one of Antarctica's larger ice rises, which is situated in the DML sector. Most of the content is a straightforward report of a field measurement campaign, where much of the motivation is to assess the ice rise's mass balance. The main conclusions are that the mass balance of the ice rise has been positive over the last decade, and that the ice rise has likely been stable for at least the last ~600 years.

The paper certainly presents data that are worth publishing and that will interest a number of readers. Down the line the data should provide a useful resource for calibrating regional mass balance measurements. The paper also represents a further case study of ice-rise conditions to complement the recent work on Derwael and Halvfarryggen. For all of these reasons it is a useful contribution.

A previous version of the paper was reviewed by two different reviewers, and the response has certainly moved the paper towards a form that is better structured and more compelling. My comments are, therefore, largely directed towards improving the efficiency and correctness of the writing.

> *We thank the reviewer for investing time on this manuscript. We found all the comments very constructive and helpful. To make sure we do not leave any more grammatical issues we used an English editing service for this revision.*

Comments

Universal changes throughout manuscript:

There is no need for the word "the" in front of e.g. Fimbul Ice Shelf, Jelbart Ice Shelf. Additionally, when used as proper nouns, e.g. in Fimbul Ice Shelf, Jelbart Ice Shelf, or even Fimbul and Jelbart Ice Shelves, then Ice Shelf/Shelves should be capitalised. Use lowercase when referring to ice shelf/shelves more generally.

Understood and corrected for. Please refer to marked manuscript for the corrections.

You introduce the acronym SMB for surface mass balance multiple times, and even sometimes use the full words again rather than taking advantage of having introduced the acronym early in the paper. Please go back through the manuscript sticking to this convention:

- Use surface mass balance (full words) in abstract.
- Introduce acronym SMB at first opportunity in main text (as you have done on P1 L16)
- Be consistent thereafter in using only the acronym SMB
- Optionally, you might choose to keep the full words "surface mass balance" in Figure captions and Section 7 Conclusions, catering for readers who might skim-read in the first instance.

The manuscript has been updated as per your suggestion. In the revised manuscript, we define SMB at P1L17 in Introduction. However, we use "surface mass balance" instead of SMB in the Abstract, section titles, and conclusions.

Please avoid split infinitives. Currently there are examples at P2 L3, P3 L10. You can search for these comprehensively by searching for the word "to".

We followed this suggestion.

Anywhere where you describe e.g. ice sheet versus ice-sheet thinning, ice shelf versus ice shelf thinning, ice rise versus ice-rise elevation, and so on, you should not use a hyphen when just referring to e.g. the ice sheet, but you should introduce the hyphen into it when describing e.g. the ice-sheet thinning. Most of the time you follow this rule well, but there are exceptions, and I recommend you search these out, and correct/confirm on a case-by-case basis. You might do this by using the search function for "ice" (and "radar", as, for example, in radar-detected features).

We followed this suggestion and made the changes. Further, the submitted manuscript has been reviewed by an English editing service.

You interchange the terms ice divide, flow divide and ice-flow divide. You could clean this up a bit by using a single term.

Corrected. We refer to it as 'ice-flow divide' once and as 'divide' afterwards in the manuscript. P5L31 onwards

Some of the writing in Section 4 oscillates between being written in the past tense and the present tense. It would generally be better written consistently in the past tense.

We have checked Section 4 (Analytical methods) to ensure that all descriptions of our past activities are in the past tense. Statements about things such as definitions and known facts are in the present. In some cases, we were not consistent originally, and these cases have been corrected.

Figure ordering

I suggest you reverse the order of Figures 2 and 3. My reasoning is explained in the line by line comments.

After carefully considering your suggestion, we have decided to keep the figure order the same. This is because the clear detection of the bed shown in Figure 2 provides base knowledge to generate Fig. 3 (bed DEM).

Line by Line

Title. I am not sure "glaciological setting" is really capturing what you do, nor is it that compelling as part of a paper's title. Would the paper be better titled: "Mass balance and stability of Blåskimen Island, Dronning Maud Land, Antarctica"? Much of the paper's focus is essentially on the present and past mass balance, with stability in the title representing the elements of the study that investigate whether the mass balance has changed significantly over time.

We agree with the reviewers' comment that there is scope for improvement in the manuscript's title. We agree with the first half of the reviewer's suggestion, but not the second half. We discuss stability of the ice rise in the manuscript, but it is only one of the main conclusions that we have made. We present ice thickness, topography, and SMB, which are all new knowledge from this region. Stability is within the scope of this paper but without numerical modeling of ice flow it is hard to rigorously conclude the stability of the ice rise. That is why we put the stability issues in discussion, not results. Our primary focus is the mass balance of the ice rise, among other glaciological characteristics. We tried and consider other alternative titles such as -

Mass balance and other characteristics of Blåskimen Island Ice Rise DML, Characteristics of Blåskimen Island Ice Rise DML, Recent thickening of Blåskimen Island Ice Rise DML etc.

But, at the end of this exercise we couldn't think of a better alternative than the present title.

I am not convinced the abstract really sells the paper all that well, nor captures the full logic of the paper. Suggested restructure:
First sentence: East Antarctica's Dronning Maud Land ice-shelf-fringed coast contains numerous ice rises that influence the dynamics and mass balance of the region.

We have largely followed the suggestion about the first sentence. But after some review, we decided not to make other major changes to the abstract.

P1, L12: Insert commas: "…shelves, together…" "…rumples), regulate…"

Corrected. P1L13

P1, L17-18: Start with: "Hence, although…" insert "areal" before "footprint" and remove *the* in L18.

Corrected. P1L18

P1, L20: Rewrite as "…evolution of ice rises and adjacent ice bodies over…"

Corrected. P1L22

P1, L23-24: More efficiently phrased as: "…Kingslake et al., 2016), supplementing ice-core-derived climate records (e.g. Mulvaney et al., 2002, 2014).

Corrected. P1L24

P2, L1: Capital L: Land

Corrected. P2L3

P2, L3: Better to substitute shape with dynamics here.

Corrected. P2L5

P2, L6: plural, beds

Corrected. P2L9

P2, L7: plural, contrasts, emplace comma after slopes

Corrected. P2L9

P2, L8: "…that both of these ice rises…"

Corrected. P2L10

P2, L8-9: "…5000 years), despite being separated by…" "and ranging across variable glaciological settings."

Rephrased as (P2L10) –

"Stratigraphic evidence shows that both of these ice rises have been in nearly steady state over the last several millennia (3000–5000 years), despite being separated by ~1200 km along the coast with variable glaciological settings."

P2, L12: This final sentence of the paragraph would be better written along the lines of: "These existing observations underscore the requirement for further detailed investigations of ice rises in DML."

Corrected. P2L16

Section 2. I felt this section could be written with a more finessed logic. I suggest the very first sentence is: "Blåskimen Island (Fig. 1a; total area 651 km^2; Moholdt and Matsuoka, 2015) is the most seaward of a series of isle-type ice rises (totally surrounded by floating ice) and promontory-type ice rises (elongated extensions of the ice sheet into an ice shelf) that partitions Jelbart Ice Shelf from Fimbul Ice Shelf.
Then discuss Jelbart Ice Shelf, fed by Schytt Glacier, then Fimbul Ice Shelf, fed by Jutulstraumen but buttressed near the western calving front near Blåskimen by the further ice rises/rumples.
Then finish with a sentence along the lines of: "In summary, ice flow to the south and north of Blåskimen Island is slow; ice flow to its east is also slowed by the ice rises and rumples on the western shear margin of the otherwise fast-flowing Fimbul Ice Shelf; and hence the fastest flow near Blåskimen Island occurs to its west where it abuts the eastern shear margin of Jelbart Ice Shelf.

The section was rewritten largely following the suggestions above. (P2L24 – P3L9).

"Blåskimen Island (Fig. 1; total area 651 km^2 (Moholdt and Matsuoka, 2015)) is the most seaward of a series of isle-type ice rises (surrounded by floating ice or ocean) that partitions Jelbart Ice Shelf from Fimbul Ice Shelf. Jelbart Ice Shelf is fed by the Schytt Glacier, which is slower by a factor of two

and narrower than the Jutulstraumen Glacier that feeds into Fimbul Ice Shelf (Rignot et al., 2011). Jutulstraumen Glacier, one of the largest outlet glaciers in DML (Høydal, 1996) is buttressed towards its western calving front by four small ice rises and rumples near Blåskimen Island. In summary, ice flow to the south of Blåskimen Island is slow, with open ocean to the north; ice flow to its east is also slowed by the ice rises and rumples on the western shear margin of the otherwise fast-flowing Fimbul Ice Shelf. As a result, the fastest flow near Blåskimen Island occurs to its west where it abuts the eastern shear margin of Jelbart Ice Shelf. This setting implies that currently Blåskimen Island alone has limited impact on the continental grounding line and ice flux from the ice sheet. However, as Favier and Pattyn (2015) demonstrated how an ice rise aids the formation of rifts and ice-shelf breakups on its seaward side, Blåskimen Island likely plays a more significant role than upstream ice rises to maintain the current calving-front position."

P3, L2-4: Conflate to a single sentence, requiring one instance of replacing surveys with measurements: "We carried out field measurements of…" "…2013-2014, comprising kinematic…" "…(Section 3.2), and firn coring…"

This paragraph has rephrased as (P3L11) –

"To estimate the mass balance of the ice rise, we made field measurements on Blåskimen Island during the austral summers of 2012–2013 and 2013–2014. The measurements included kinematic and static GPS surveys (Section 3.1), shallow- and deep-sounding radar profiling (Section 3.2), as well as firn coring and borehole temperature measurements (Section 3.3). The location of these measurements is shown in Fig. 1b."

P3, Opening section. I think this small opening paragraph would benefit from a small expansion explaining WHY you gathered each of the named datasets. Currently readers are only being fed this information later in the manuscript.

An opening line has been added to the paragraph and some other minor changes were made (P3L11).

"To estimate the mass balance of the ice rise, we made field measurements on Blåskimen Island during the austral summers of 2012–2013 and 2013–2014. The measurements included…"

P3, L10: Introduce comma: "…ice rise, and…"

The sentence has been rephrased. P3L21 –

"To locate the ice rise's summit, we ran additional surveys near the summit and in the eastern part of the ice rise where satellite imagery shows surface lineations (light grey feature over dark grey in Fig. 1b)."

P3 P15: More efficiently phrased as: "…(Matsuoka et al., 2012b), and 90 reoccupied in January 2014, the remaining 7 being lost to snow burial or found to be tilting by > 20°. Note that this no longer specifies that 6 were buried and one tilted but I suspect readers have negligible interest in that specificity.

Rephrased as suggested (P3L23) –

"The stakes were occupied for ~20 minutes to determine their lateral positions (e.g., Conway and Rasmussen, 2009; Matsuoka et al., 2012b), and 90 were reoccupied in January 2014, the remaining 7 being lost to snow burial or found to be tilting by > 20°."

P3 L21: Remove comma: "…kinematic and…"

Corrected. P4L4

P3 L22: …using TRACK software, part of the GAMIT/GLOBK GPS package (Herring…"

Corrected. P4L5

P3 L29: sp. descent

Corrected. P4L13

P3 L31: Insert "a": "…operated a GSSI…"

Corrected. P4L15

P3 L32: "…Hawley et al., 2014). Both radar surveys…"

Corrected. P4L16

P4 L13: I think "record" is more suitable here than "develop."

Corrected. P4L29

P4 L21: "Hereafter we refer to mean density as…"

Corrected. P5L7

P4 L24: "…estimating SMB below 3 m depth, we…

Sorry that you misunderstood. We meant to refer to the SMB calculation later in the manuscript. The sentence has been corrected to be clearer. P5L11 –

"We then used the bilinearly interpolated surface density to estimate SMB."

Section 4.1
Nowhere as the 2x methods for determining SMB are introduced is there a helpful and immediate clarification that the two methods have relative merits in terms of the simplicity of the measurements versus the timescales of information they address. I'd like it to be made more upfront in the opening to this section that the stake method is undertaken because it can inform quickly on the broad patterns of change between 2013 and 2014, albeit with an overall uncertainty of 6%, but that the radar method can give a longer-term view.

Added the following sentences to as per your suggestion (P5L16) –

"The stake method is simpler and provides insight on SMB pattern over the ice rise for the period of 2013-2014. The radar method has higher uncertainties, but provides a longer-term view of past SMB patterns."

P4 L31: "…accounting for snow…"

Corrected. P5L20

P5 L5: "…reflectors is solely…"

Corrected. P5L26

P5 L6: "Thus the shallow-ice…" "…when the depth…"

The sentence has been rephrased. P5L27

"With these assumptions, the shallow-layer approximation holds when the depth h (ice equivalent) of a radar reflector is much smaller than the local ice thickness H (h<<H)."

P5 L11: "…which have been found…"

Corrected. P5L33

P5 L12: Substitute "Such upward" with "Raymond"

Replaced 'such' with 'similar' as the observed shallow arches are similar to Raymond arches but are not the same. P6L1

P5 L14: "…demonstrated that the amplitude of Raymond arches…"

Corrected. P6L3

P5 L16: There's no need to refer to Figure 2 here. The main effect is to distract the reader. It seems that your purpose in referring to Figure 2 at this point is simply to illustrate a typical Raymond arch, but I strongly suspect your target readership knows what this is already. If they don't, they should be referring to Raymond 1983!

The observed upward arches in the shallow radar are not the same as Raymond arches due to a different mechanism of formation, although they are both 'upward arches'.

In these lines (P5L31 – P6L5) we are discussing and comparing ('similar arches') these distinct features observed in shallow and deep radar profiles. We feel while reading these lines, the reader will be curious to see these features first hand and that is why we cite figure 2 here.

For completeness, we cited Fig 2c (P5L32) when we first talk about Raymond arches.

P5 L26 and L28: Replace "is" with "was".

Sentence rephrased as (P6L18) –

"The first method accounts only for vertical variations in density and ignores any lateral variations."

P5 L28: "method is to invert simultaneously for spatial variations in…" and cut all words from altogether to the citation.

Sentence rephrased as (P6L19) –

"The second method involves simultaneously inverting for spatial variations in density, temperature, and SMB (Brown and Matsuoka, in prep)."

The only explanation (as such) you give for the inversion is to refer to an in prep manuscript. There is no description of the technique given at all. This issue was also raised by Reviewer#1 first time around, and I don't think you have addressed it. If you are going to use results from this technique at all in the paper, there needs to be some more information on it. Is the Brown/Matsuoka inversion at least part derived from an earlier method that can be cited here?

We have tried to clarify this method in more detail through these sentences – (P6L19) – There is no prior work using an optimization inversion route in our way so we didn't add a reference.

"The second method involves simultaneously inverting for spatial variations in density, temperature, and SMB (Brown and Matsuoka, in prep). It uses an optimization inversion routine to solve for the best fit between a steady state firn density model (Herron and Langway, 1980) and the measured two-way travel times to multiple isochrones identified in shallow-radar profiles. Our optimization routine is constrained by surface densities measured at 13 locations along the shallow-radar profile as well as the measured depth- density profile along the 23 m long firn core."

P6 L8: "…melting, as a one-dimensional…"

Sentence rephrased as (P7L5) –

"As a one-dimensional thermomechanical model (Neumann et al., 2008) shows no basal melt for the geothermal-flux estimate in this region (57 mW m^{-2}; Fox Maule et al., 2005), we ignored basal melting."

P6 L9: The author's full surname(s) – admittedly an unusual form – is Fox Maule (n.b. no hyphen). Thus it should appear as Fox Maule et al here, and should be listed in the reference list as Fox Maule, C.

Corrected, both text and the citation. P7L6 (not highlighted as LatexDiff has trouble with citation changes)

P6 L9: I think it would be appropriate to insert a word like "Moreover," to start this sentence.

Added. P7L7

P6 L10: I think that here, as with P5 L16, there's not a big need to refer to Fig. 2 yet. The flow of the paper would be improved by having people first look at the results figures in the results section.

We agree that it is not necessary to mention figure 2 here in the method section. But, as we have already referred to this figure once by this point in the manuscript, we prefer to continue to refer to it here for the benefit to the curious reader.

The figure 2 was not switched with figure 3 and was cited early in the method section because of two reasons -

- *As the clear detection of the bed shown in Figure 2 is the base knowledge to generate Fig. 3 (bed DEM).*
- *As Figure 2 is cited at a point where we are discussing two kinds of upward arches which look similar but formed differently. And reader could benefit looking at figure 2 at that point.*

P6 L13: Insert and: "…column, and γ.."

Corrected. P7L11

P6 L18: "…over a non-sliding bed and using the shallow-ice…"

Corrected. P7L17

P6 L20-21: "…Drews et al., 2015), giving γ between…"

Corrected. P7L20

P6 L17-L28: Make all this a single paragraph.

Corrected. (P7L16 – P7L29)
(It is not showing properly in the marked manuscript due to a bug in the Tex software, but un-marked version has these as one paragraph.)

P6 L22-23: Suggest: "However, because the ice is not isothermal and, near the ice divide, the shallow-ice approximation is also invalid, in reality the range of γ is wider."

We mention these points, though write it a little differently (P7L21-P7L21) –

"However, due to ice-temperature variations and ice-divide effects, the latter of which invalidate the shallow-ice approximation, the range of γ should be wider."

P6 L31: "For the thermomechanical…"

Corrected. P7L32 – P8L3

"Also within 10H of the divide, the case of thermomechanical flow gives 0.69 ≤ γ ≤ 0.86 Hvidberg (1996) and the case of isothermal axisymmetric radial flow gives 0.54 ≤ γ ≤ 0.76 Hvidberg (1996)."

P7 Section 4.2.2. I would consider this section to be more logically ordered throughout as (1) flowband method, (2) polygon setup, and (3) grid setup. The first represents the most direct reliance on the field measurements, the other two rely more on interpolation to expand the coverage. I note that in your results (Section 5) you follow this order in the text, so it would be better streamlined writing to discuss the method in the same order here.

We agree and reordered the section as suggested. Now we mention flowband setup first, polygon setup second, and grid setup last (P8L21 – P8L19)

P8 L14: Here, if you agree with my earlier suggestions that there has not yet been a need to refer readers to the radargrams in Fig. 2, then it would be better to order the current figures so that Fig. 2 is now the 3 panel figure of surface/bed/velocities. Hence change text here to refer to Fig. 2a.

We agree and changed the order of figure panels accordingly; (a) flowband, (b) polygon, and (c) grid setups.

P8 L20 and Fig. 3b, now suggested to be Fig. 2b: Perhaps add the profile numbers 1-1', 2-2' etc as also marked on Fig. 1b. Figs. 2 and 3 will be located close to each other in the final paper, so this might save readers having to flick back to Fig. 1 to locate the radargram positions. If you do this, then you should change the locational reference in the text to "2-2' in Figs. 1b and 2b".

We have marked the radar profiles in the Figure 3b as suggested.

P8 L21, L22: Here it now makes logical sense that you introduce readers for the first time to the plots of surface slope and radargrams respectively. But they would now be labelled Fig. 3a, b, c.

As we responded above, we decided not to change the figure order, because the clear detection of the bed shown in Figure 2 is the base knowledge to generate Fig. 3 (bed DEM). As well as Figure 2 is cited at a point where we are discussing two kinds of upward arches which look similar but formed differently. And reader could benefit looking at figure 2 at that point.

Below this point in the paper, swap all references to Figs 2 and 3.

P9 L13: Not really sure why it's especially specified here that the study area is 20 x 20 km. You've already stated the area in Section 2, and a reader can see the area on Figs. 1b, 3, 4. It just seems to make the sentence overlong. There does, however, seem to be a discrepancy between the 20 x 20 km of these figures and the value of 651 km^2 written in P2 L19 (and in P11 L9). How is the smaller area of 651 km^2 defined specifically?

The area of the ice rise is indeed 651 km^2. The term 20 x 20 km was used to give a first order idea during talks etc and should not have been included in the manuscript. Now removed. (P11L5)

P9 L14: Is it not more correct to note that the main contrast is between the northwest and the southeast?

Yes. Now updated. (P11L7)

P9 L23: "…are controlled primarily by SMB versus the Raymond effect…" "we measured the amplitudes…"

Corrected. Now rephrased as (P11L16) –

"To judge whether the reflector depths are controlled primarily by SMB or the Raymond effect…"

P9 L24: Extra "the" needed x2: "We used the two deeper arches of the three that we used for SMB…"

Corrected in the rephrased sentence (P11L17) –

"Due to the shallowest reflector having insignificant amplitude, we used just the two deeper reflectors of the three that were used for SMB estimates."

P9 L29: represent (not represents)

Yes. P11L24

P10 L16-19 and Figure 6. I suggest rearranging Fig. 6 panels so that panel a is flowband, panel b polygon and panel c grid. This would make all of Section 4.2, 5.3 and Fig. 6 consistently ordered. You could easily introduce some more specific references to Fig 6a, b and c where relevant in L16-19.

Figure 6 panels haven been rearranged.

P10 L21-23: This reads like a sentence that should have been used back in Section 4.2.

Agree. Now moved to Section 4.2 (P8L18).

P10 L25: gives

Corrected. P12L26

P10 L29: southeasternmost?

Yes. Corrected. P12L33

P10 L31-32: I'm not sure I follow what you mean by thickening and thinning in this sentence. Does this refer to the trend for mass balance to increase/decrease upslope/downslope in slopes A and F? I see that in slope A the lowermost polygon has a much lower mass balance than the upper two polygons in slope A, but I do not see the reverse trend in slope F – in slope F the mass balance looks pretty similar in each polygon. I see that the average mass balance of slope A is lower than the average mass balance of slope F, although whether the average mass balance is actually the lowest of all slopes is not clear, because slope D has low values too. Similarly, it's not clear (if this is what you're trying to say) that slope F has the highest mass balance of all slopes, at least from the information one can draw from Figure 6.

We apologize for the confusion. After updating figure 6 with the different SMB dataset after the first review, the slope F does not show the high SMB in the lower slopes as it did before. We should have updated the text accordingly after the update in the dataset. Now this sentence has been removed. The updated paragraph (P12L31 – P13L5)-

"For polygon and grid setups, all the columns show positive mass balance over the full γ range, except for southeasternmost downstream polygon A3 (the slope-direction codes are shown in Fig. 6b). Along slopes C, E and F, mass balance does not vary significantly along the slope, whereas mass balance of polygons along slopes A, B, and D is more variable. For the Flowband setup, six of nine columns show positive mass balance, with columns CD3 and DE1 (see Fig. 6a for the slope-direction codes) being very close to balance. Column DE3 has negative mass balance in the northwest downstream, a region where the estimated flow divergence is anomalously large."

P11 L1: Suggest rephrasing: "Together, the measurements show that Blåskimen Island had positive mass balance between 2005 and 2014."

We rephrased the sentence as (P13L6) –

"In summary, the measurements show that Blåskimen Island had positive mass balance between 2005 and 2014."

P11 L2-4: Another opportunity to re-order.

Done. P13L7-P13L11

P11 L4: Use the symbol for gamma as you have done elsewhere.

Yes, Corrected. P13L10

P11 L13-L24: There are some missing words in the current sentence but in any case there's no real need to specify that your DEM comes from GPS at this stage of the paper. Suggest: "Our detailed surface DEM (Fig. 2a) reveals a number of surface topographic features that are smoothed over in continent-wide DEMs (e.g. Bamber et al., 2009; Fretwell et al., 2013). It confirms, for example, that the lineations in satellite imagery observed in satellite imagery over Blåskimen Island correspond to surface undulations (c.f., Goodwin and Vaughan, 1995)" N.b., the c.f. is important, because Goodwin and Vaughan didn't refer to this location. Start the final paragraph essentially with a rewritten version of the current paragraph's second sentence: "We further note that the summit height of Blåskimen Island is 24-40 m higher in our DEM compared with the lower resolution DEMs"

…. However, can you clarify for sure that this is not a consequence of the different products being referenced to different vertical datums?

I think it is disingenuous to describe the Bamber/Bedmap2 as an "inaccurate description of topography". It's lower resolution, which is not the same thing at all.

Thank you for pointing out the possible issue; we re-visited the issue more carefully. First, different geoid models are used for previous work, which should be corrected accordingly. However, different geoid datasets cannot be the main reason of the apparent difference; geoid heights of the cell nearest to Blåskimen Island are 14.4 m (GL04C used in BEDMAP2/Bamber DEM), and 13 m (GOCE, used in our work). Second, different continent-wide DEMs describe the shape and height of Blåskimen Island differently. For example, BEDMAP2 surface elevations match well at the summit with the data (difference: 10 m), but they are quite different in the flank (100 m). Bamber DEM is offset from the observations by 80-100 m. These numbers do not reflect statistical significance of these DEMs and we do not assess uncertainties of these DEMs using these numbers. However, we want to briefly mention such possibly large difference over ice rises and emphasize the need of field data to better calibrate or validate DEMs. To reflect these points, the text was updated as follows (P13L20-P14L6)-

> *"Our detailed surface DEM (Fig. 3a) reveals a number of surface topographic features that are smoothed over in continent wide DEMs. For example, two widely-used DEMs (Bamber et al., 2009; Fretwell et al., 2013) show different topography of the ice rise and elevations are off from our local DEM by 10-100 m at different places. Ice rises have much steeper slopes than the continental slope (Fig. 2a), which inherently requires high-spatial resolutions to accurately represent the topography. This missing detail could affect modelling SMB and surface density. Lenaerts et al. (2014) demonstrated that elevated topography associated with an ice rise causes orographic precipitation and the resulting precipitation shadow not only over the ice rise, but also on the adjacent ice shelves. Such variations could result in anomalous firn-density estimates over the ice shelves, which would result in ill-posed estimates of freeboard thickness and the resulting long-term changes of adjacent ice shelves. Our local DEM confirmed that lineations in satellite imagery over Blåskimen Island appear where the surface slope has greater variability, with most lineations being associated with uneven bed topography. Such an association was originally proposed over Fletcher Promontory Ice Rise by (Goodwin and Vaughan, 1995). This agreement supports the use of satellite imagery as a remote means to explore first-order surface and bed topography."*

P11 L28: This is an inappropriate use of "inferring". You could replace it with: "from which we infer"

Corrected. P14L10

P11 L29: vary should be varies.

Sentence rephrased (P14L11) –

"SMB averaged over this period has a mean of 0.81 m a^{-1}, but varies along the radarprofiles between 0.71 m a^{-1} (first quartile) and 0.93 m a^{-1} (third quartile)."

P12 L1: Suggest: "…SMB has been observed on other Antarctic ice rises. For example, King (2004) showed…"

Corrected. P14L14

P12 L7: "The net impact…" "…coast has been examined using the RACMO2…"

Corrected. P14L21

P12 L16: "…Derwael Ice Rise, where it was attributed to wind…"

Corrected. P14L33

P12 L29: Here, if you do not already have data or a different publication to cite that gives the modelling results, you would be better advised to write: "…which are likely Raymond arches, though ice-flow modelling would be required to confirm this interpretation."

We agree. Now corrected. P15L15

P13 L13-L20: I'm not convinced this paragraph is really saying anything that couldn't have been said in the absence of all your new data. Certainly the final sentence is inappropriate for a published paper.

We have removed this paragraph (P16L01- P16L8) and moved some of its content to section 2 (P3L6) where Blåskimen Island is introduced.

P13 L22: Past tense: "investigated"

Changed, changed the sentence to past tense as (P16L10) –

"We used geophysical methods to investigate Blåskimen Island, one of the larger isle-type ice rises at the calving front at the intersection of Fimbul and Jelbart Ice Shelves on the DML coast."

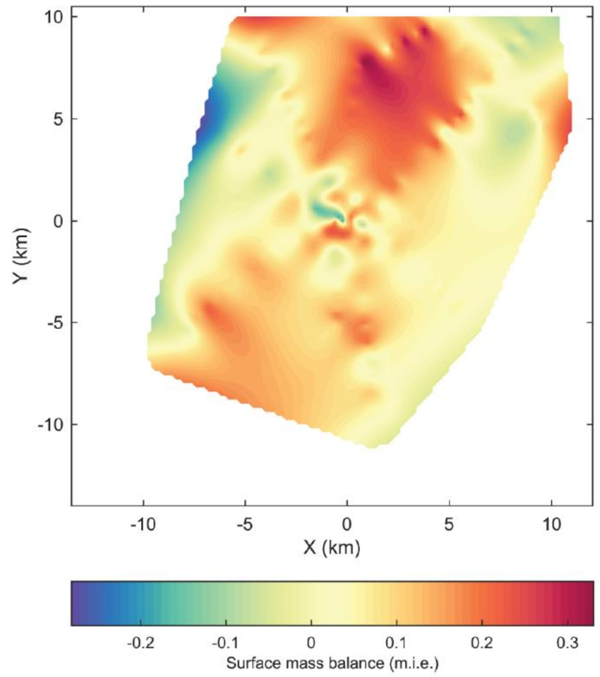
Figure 1
Ice Shelf should be written with capital letters in both labels on Fig. 1a.
Since you mention Schytt Glacier in the main text this may also be worth marking on Fig. 1a.

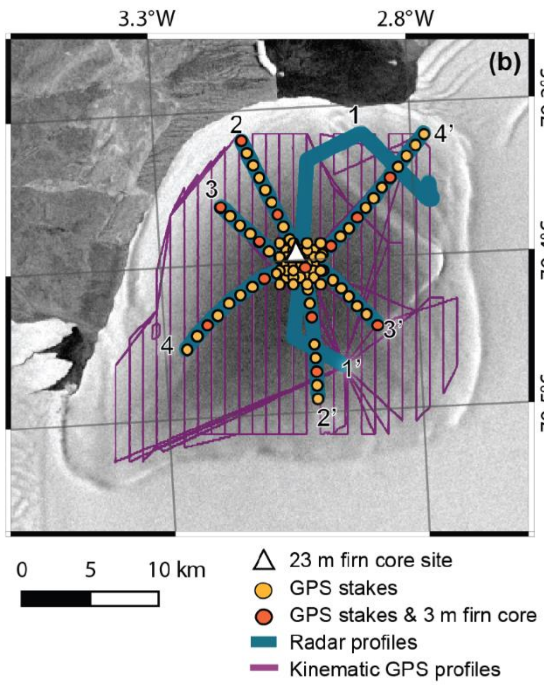
Corrected.

Figure 4

Did you think about producing a difference map as a third panel, to help in the general comparison of the results?

The difference plot of stake-derived SMB and radar-derived SMB is shown here with Fig. 1b to present data availability from the stake and radar methods –





We feel this SMB comparison suffers with two reasons. First, the spatial coverage of these two datasets are different. For example, the maximum difference appears North, where no radar data exist. Second, both the datasets deal with different time periods.

Due to these reasons, we decided, not to include this panel in the revised manuscript.

Review #2

I reviewed a previous version of this manuscript. I outlined my appreciation for the importance of glaciological work on ice rises in the previous review. Here I comment on the authors' responses to my original comments (https://doi.org/10.5194/tc-2017-61-RC1). I also highlight some of the typos that are still present.

In the attached annotated copy of the response letter I have commented on the responses. Below are additional specific comments. It would be useful if the authors noted where in the revised manuscript specific revision have been made. Also, unhelpfully, there are several differences between the quoted text in the responses and the revised text. I have found many grammatical errors. But I have only documented some of those that are in sentences revised in response to my previous comments.
(Page and line numbers refer to the non-marked up version of the revised manuscript).

We really appreciate the amount of constructive corrections and suggestions you provided in the first review. And we really apologize to have caused you inconvenience with our responses. We did multiple checks to our response and ended up making some last moment changes, which led to being a mismatch in the response letter and the revised manuscript. This time we have been extra *careful and have only included the quotes from the manuscript at the very end of the process. Also, we have tried to include the position of all the changes even for minor changes.*

Specific comments

P317: Remove extra 'the' here.

We have rephrased the sentence as (P4L4)-

"Instantaneous kinematic and average static-rover station locations were determined relative to the base stations for each field season using TRACK software, part of GAMIT/GLOBK GPS package (Herring et al., 2010)."

P8L16-17: "…giving a relatively dome-shaped topography to the ice rise." reads poorly to me.

Corrected. (P10L6)
Now " giving a dome-like shape to the ice rise "

P4L21: "Hereafter we call mean density in the top 3 m as surface density." Suggest replace 'call' with 'refer to".

Corrected as suggested. P5L7

The reviewer provided comments marked on the response letter. Below, we respond to relatively major comments first and minor ones afterwards.

Reviewer: I am not sure I see the relevance here of the parentheses about wind direction.

Response: Previous studies show that SMB is largely related to the local slope (e.g. King (2004)), as wind is faster over a steeper slope. We didn't see this relationship clearly in our data (Fig. 2a) but we think that this is because the wind direction is oblique to the profile we sampled. With the text in parenthesis we want to clarify that as the slope in discussion is not aligned along the prevailing wind direction. Therefore, the observed result of 'no clear relationship' does not necessarily disagree with previous studies. No change was made in the manuscript.

Reviewer: The point is that reader of the paper will not necessarily make this link with more detail. When the reference to wind direction comes out of no where like this, it is hard to recall the background that you describe here without some clues. More details are needed here.

This sentence is more closely related to individual mechanisms that make up the SMB. Therefore, we moved this sentence to the paragraph immediate above where we discuss wind-related mechanisms. In this way, we can separate our discussion on individual processes to make up SMB in one paragraph (P14L14-P14L22) and overall SMB distribution mostly in comparison with modeled SMB in the paragraph immediately below (P14L23-P14L33).

Reviewer: The surface velocity measurements are described as a surface velocity field here, when they really appear as just point measurements in figure 2c, rather than a field.

Response: We used large number of point measurements of the ice-flow vector to estimate the flow field. We think that the manuscript is clear enough

Reviewer: Where is this described or plotted? All I see are the point measurements. To me a field implies some kind of continuity of date coverage. Therefore I disagree that the data plotted in Fig. 3c is a flow field.

We have now replaced the word 'field' with 'velocities' and 'velocity measurements' as applicable throughout the manuscript. E.g. P2L21, P3L24, P10L2, P10L28 etc

Reviewer: The estimate of the vertical uncertainty of ±5m could be more fully explained here. The center frequency of the deep radar was 2 MHz, corresponding (I think) to a wavelength of c/ni/2x106 = 84.2 m, where c is the speed of light and ni is the refractive index of ice. This wavelength is considerably more than your estimated uncertainty in digitizing the bed reflector. Is the higher precision achieved due to the signal being quite broadband? Perhaps this can be explained in more detail, as one might expect a bed reflector imaged with an 84 m wavelength radar to manifest as a layer thicker than 5 m.

Response: The center frequency of the deep-sounding radar is 2 MHz, giving the wavelength in ice approximately 84 m. Therefore, this radar is not capable to distinguish two objects that are separated less than 42 m (half of the wavelength). Nevertheless, this radar is capable to detect the range to the target more precisely. We sampled returned wave at 100 MHz, or every 10 ns. Over this period, radio wave travels about 2 m.

Reviewer: This explanation makes sense, but there is no indication of where this has been explained in the revised text.

The response we provided in the letter is mainly clarifying the difference between depth accuracy and resolutions. Although it is useful information, adding this clarification in length to the manuscript distracts the flow of the paper. Therefore, we decided not to include it in the revised manuscript.

(Previous comments not included as its not relevant to the comment below)

Reviewer: In the text you now use the shallow-ice approximation (SIA), where you previously used shallow-layer approximation. SIA is a term already used to describe an approximation to the Stokes Equations for ice-sheet model which is different than neglecting vertical strain for shallow radar layers. So I support the original terminology: shallow-layer approximation.

It is our mistake to change both "laminar flow" and "shallow-layer approximation" to "shallow-ice approximation". The reviewer suggested to change only the former and it is what we wanted to make. However, in the last editing process, both of them were changed to Shallow-ice approximation. We sincerely apologize for this error. Now, shallow-ice approximation is used to explain the ice flow, but shallow-layer approximation is used to explain the assumption to derive the SMB using radar data.

Other comments –

This is different than in the text.

It would be useful if you said where these changes have been made in the marked manuscript

There some differences between the quoted text below and the text in the marked manuscript.

We apologize for this mismatch. We have been a lot more careful to avoid such issues this time.

replace with "towards the east" or "eastwards"

We have rephrased large part of this section. Relevant sentences at – (P2L24-P3L9)

OK. Well change the start of this sentence to "The position of each stake...." then.

delete ('the')

We have rephrased the sentence as (P3L28) –

"The stakes were occupied for ~20 minutes to determine their lateral positions (e.g., Conway and Rasmussen, 2009; Matsuoka et al., 2012b), and 90 were reoccupied in January 2014, the remaining 7 being lost to snow burial or found to be tilting by > 20°."

"We then used the depth profiles of the density along the radar profile to estimate laterally variable firn corrections."

Is a word missing here? Perhaps "with"? (between 'along' and 'the')

The sentence rephrased as – (P4L24)

"The correction was estimated using the modeled depth profiles of the density along the radar profile based on firn-core density observations and shallow-radar data, as further discussed in section 4.1."

Delete ('we')

A word is missing here.

Sentence rephrased. (P4L29) –

"To record the stratigraphy (visual, chemical, isotopic, and dielectric), we drilled a 23 m long firn core near the ice-rise summit. The core was dated back to 1996 by counting annual cycles of oxygen isotopes and by identifying volcanic horizons using non-sea-salt sulphate data (Vega et al., 2016)."

Word missing still.

Added 'the'. P10L7

replace with 'with'

Corrected. P9L4

Glaciological settings and recent mass balance of Blåskimen Island in Dronning Maud Land, Antarctica

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Abstract. The ice-shelf-fringed coast of Dronning Maud Land ~~coast~~ in East Antarctica ~~has~~ contains numerous ice rises that ~~very likely control~~ influence the dynamics and mass balance of ~~this~~ the region. However, only a few of these ice rises have been investigated in detail. Here, we ~~report~~ present field measurements of Blåskimen Island, an isle-type ice rise adjacent to ~~the~~ Fimbul Ice Shelf. ~~Blåskimen Island~~ This ice rise is largely dome shaped, with a pronounced ridge extending to the southwest from its summit (410 m a.s.l.). Its bed is mostly flat and about 100 m below the current sea level. Shallow radar-detected isochrones dated with a firn core reveal that the surface mass balance is higher on the southeastern (upwind) slope than the northwestern (downwind) slope by ∼37%, and this pattern has persisted for at least the past decade. ~~Arches~~ Moreover, arches in radar stratigraphy suggest that the summit of the ice rise has been stable for ∼600 years. Ensemble estimates of the mass balance using the ~~input-output~~ Input-Output method show that this ice rise has thickened by 0.12–0.37 m ice equivalent per year over the past decade.

1 Introduction

Around 74% of the Antarctic coastline consists of floating ice shelves fed by outlet glaciers and ice streams (Bindschadler et al., 2011). These ice shelves, together with numerous pinning points (ice rises and rumples), regulate the outflow of the grounded ice (Dupont and Alley, 2005; Matsuoka et al., 2015; Fürst et al., 2016). Embedded into ~~the~~ an ice shelf, ~~ice rises create~~ an ice rise creates a zone of compression upstream of the ice rise ~~which~~ that buttresses the ice shelf (Borstad et al., 2013). However, downstream of the ice rise the tensile forces leave a weak region subject to crevasses and thinner ice shelves (Favier and Pattyn, 2015). ~~Ice~~ Also, ice rises strongly influence regional surface mass balance (SMB) (Lenaerts et al., 2014) and can significantly alter the timing of deglaciation of the ice sheet (Favier and Pattyn, 2015; Favier et al., 2016). ~~Although~~ Hence, although relatively small in areal footprint, ice rises can have far-reaching effects on ~~the Antarctic ice sheet~~ Antarctic ice-sheet dynamics.

Ice rises are also a useful resource for investigating the evolution and past climate in the coastal region. Englacial (isochronous) stratigraphy detected using radar has been widely used to constrain the evolution of ~~the ice rise~~ ice rises and adjacent ice ~~body~~ bodies over the past millennia (Conway et al., 1999; Nereson and Waddington, 2002; Hindmarsh et al., 2011; Siegert et al., 2013; Drews et al., 2015; Kingslake et al., 2016), supplementing ice-core-derived climate records (e.g. Mulvaney et al., 2002, 2014).~~The knowledge of the evolution of an ice rise is crucial to retrieve reliable past regional climatic changes,using ice cores drilled through it (Mulvaney et al., 2002, 2014).~~

The 2000 km long coastline of Dronning Maud ~~land~~ Land (DML, 20°W–45°E), East Antarctica, consists of numerous outlet glaciers and ice shelves punctuated by some 30 ice rises (Matsuoka et al., 2015). These ice rises most likely contribute significantly to the ~~shape~~ dynamics and mass balance of this region. In addition, ~~they present an opportunity to better understand~~ their study provides clues to the evolution of this ~~data sparse~~ data-sparse region (Mackintosh et al., 2014). So far, only two ice rises have been investigated in DML: Derwael Ice Rise (26°E) in Roi Baudouin Ice Shelf (Drews et al., 2015) and Halvfarryggen Ice Dome (6°W) between Jelbartisen and Ekstromisen ice shelves (Drews et al., 2013). Both ice rises are grounded on flat ~~bed~~ beds $\sim$200 m below the current sea level, show large SMB ~~contrast across upwind/downwind slopes~~contrasts across upwind–downwind slopes, and have dynamic characteristic times of hundreds of years. Stratigraphic evidence shows that both of these ice rises have been in nearly steady state over the last several millennia (3000–5000 years)~~. These ice rises are~~ , despite being separated by $\sim$1200 km along the coast ~~, where glaciological settingsare variable~~with variable glaciological settings. For example, along the DML coast between the two ice rises, SMB can vary by at least a factor of two, depending on surface topography, storm tracks and wind direction (King, 2004; Lenaerts et al., 2014). This region also consists of several ice shelves and outlet glaciers with flow speeds varying by a factor of four (Rignot et al., 2011). ~~Ice rises in these varying settings can evolve and impact adjacent ice shelves differently and hence needs to be investigated~~These existing observations underscore the requirement for further detailed investigations of ice rises in DML.

~~We carried out~~ To elucidate the current status and past evolution of this coastal region, we made field measurements of Blåskimen Island, an isle-type ice rise located west of the Fimbul Ice Shelf at the calving front (Fig. 1a)~~, to elucidate the current status and past evolution of this coastal region. Here, we present~~ . We present here surface and bed topography, ~~surface flow field, and surface mass balance~~ surface-flow-velocity measurements, and SMB of Blåskimen Island. Our analysis of these data implies that the ice rise has thickened by 0.12–0.37 m a^{-1} (ice equivalent) over the past decade.

2 Blåskimen Island

Blåskimen Island ~~has a total area of~~ (Fig. 1; total area 651 km^2 ~~(Fig. 1a; Moholdt and Matsuoka, 2015). It is located between the Fimbul and Jelbart Ice Shelves near the calving front. Both of these ice shelves flow around several isle-type ice rises (isolated from the ice sheet by an ice shelf) and promontory-type ice rises (elongated extension of the ice sheet into an ice shelf). The~~ (Moholdt and Matsuoka, 2015)) is the most seaward of a series of isle-type ice rises (surrounded by floating ice or ocean) that partitions Jelbart Ice Shelf from Fimbul Ice Shelf~~is mainly fed by the Jutulstraumen Glacier, one of the largest outlet glaciers in DML (Høydal, 1996). The~~ . Jelbart Ice Shelf is fed by the Schytt Glacier, which is slower by a factor of two and narrower ~~,~~ than the Jutulstraumen Glacier ~~(Rignot et al., 2011).~~ that feeds into Fimbul Ice Shelf (Rignot et al., 2011). Jutulstraumen Glacier, one of the largest outlet glaciers in DML (Høydal, 1996) is buttressed towards its western calving front by four small ice rises and rumples near Blåskimen ~~Island, along with two more ice rises upstream, Novyy Island and Lejtenanta Smidta, separate these two ice shelves. The ice between Blåskimen~~ Island~~and these ice rises moves very slowly~~

~~($\ll$ 10 m a^{-1} Rignot et al., 2011). In addition, there are four smaller ice~~. In summary, ice flow to the south of Blåskimen Island is slow, with open ocean to the north; ice flow to its east is also slowed by the ice rises and rumples ~~near the calving front of the~~ on the western shear margin of the ~~fast-flowing portion of the~~ otherwise fast-flowing Fimbul Ice Shelf~~(Moholdt and Matsuoka, 2015). Thus towards east,~~. As a result, the fastest flow near Blåskimen Island ~~is surrounded by much slowly moving ice whereas~~ occurs to its west where it abuts the eastern shear margin of ~~the fast flowing part of the~~ Jelbart Ice Shelf~~towards west.~~. This setting implies that currently Blåskimen Island alone has limited impact on the continental grounding line and ice flux from the ice sheet. However, as Favier and Pattyn (2015) demonstrated how an ice rise aids the formation of rifts and ice-shelf breakups on its seaward side, Blåskimen Island likely plays a more significant role than upstream ice rises to maintain the current calving-front position.

3 Field measurements and data processing

~~We carried out field surveys of~~ To estimate the mass balance of the ice rise, we made field measurements on Blåskimen Island during the austral summers of 2012–2013 and 2013–2014. ~~It~~ The measurements included kinematic and static GPS surveys (Section 3.1), shallow- and deep-sounding radar profiling (Section 3.2), as well as firn coring and borehole temperature measurements (Section 3.3). The location of these measurements is shown in Fig. 1b.

3.1 Kinematic and static GPS surveys

To develop digital elevation models (DEM) of the ~~ice rise~~ ice-rise surface, we conducted kinematic GPS surveys using Trimble dual-frequency receivers. Two units were installed near the ice-rise summit, one acting as a base station, with one for redundancy. Five rover stations were mounted on snowmobiles ~~, which moved at a speed of~~ that moved at $\sim$15 km h^{-1}. Our survey resulted in ~~surface elevation measurements at the~~ surface-elevation measurements with an average interval of $\sim$4 m along the survey transects, the latter which are spaced 0.8–1 km from each other. ~~Additional surveys were carried out in the vicinity of the summitto precisely determine the summit position of the ice rise~~ To locate the ice rise's summit, we ran additional surveys near the summit and in the eastern part of the ice rise where satellite imagery shows surface lineations (light grey feature over dark grey in Fig. 1b).

To measure the surface-flow ~~field~~velocities, we installed 3 m long hollow aluminium stakes at 97 locations on Blåskimen Island. The stakes were installed $\sim$1 m into the snowpack~~without any anchor resisting vertical motion~~. We did not use any anchor to resist vertical motion of the stake. Out of these, ~~55~~ 56 stakes were installed along the 6 steepest descent paths as determined with the surface DEM. ~~The other 41 stakes were installed in the vicinity (<~~ To discern small ice-flow speeds within 2.5 km ~~)~~ of the summit~~to better resolve small ice-flow speeds~~, we installed the other 41 stakes there. The stakes were occupied for $\sim$20 minutes to determine their lateral positions (e.g., Conway and Rasmussen, 2009; Matsuoka et al., 2012b)~~. The position of each of the stakes was measured in January 2013. In January 2014 we remeasured the positions of the~~, and 90 ~~of these stakes. Six stakes were buried and one found heavily tilted (more than $\sim$~~ were reoccupied in January 2014, the remaining 7 being lost to snow burial or found to be tilting by > 20°~~). We did not use GPS-measured vertical positions to determine~~

~~ice-thickness changes, because of~~ . Due to possible motion of the stakes relative to the firn and firn densification, we did not use GPS-measured vertical positions to determine ice-thickness changes. Nevertheless, we measured their heights to the snow surface to estimate ~~surface mass balance (SMB)~~ SMB over the year.

Instantaneous kinematic ~~,~~ and average static-rover station locations were determined relative to the base stations for each field season using TRACK software~~package~~, part of ~~the~~ GAMIT/GLOBK GPS ~~positioning software~~ package (Herring et al., 2010). Base-station positions for each field season were determined using the Canadian geodetic Precise Point Positioning system (CSRS-PPP; https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php). These base stations moved negligibly over the 5 days of GPS campaigns each year ~~;~~ (i.e., less than the $\sim$1 cm lateral error of each GPS location~~($\sim$1 cm laterally)~~). To convert heights above the WGS84 ellipsoid to heights above local sea level, we subtracted 13 m of geoid height uniformly provided by the GOCE gravity product (https://earth.esa.int/web/guest/data-access/browse-data-products/-/article/goce-gravity-fields-5777).

3.2 Ice-penetrating radar profiling

~~We~~ To reveal the ice thickness and englacial isochronous stratigraphy, we collected common-offset radar transects along four of the ~~steepest-decent~~ steepest-descent paths concurrent with the GPS stake locations. These radar transects were collected with a ~~2-MHz~~ 2 MHz ground-based radar system with ~~resistively-loaded~~ resistively loaded dipole antennas (Matsuoka et al., 2012a)~~to reveal the ice thickness and englacial isochronous stratigraphy~~. We also operated a GSSI/SIR3000 radar with ~~400-MHz~~ a 400 MHz antenna to detect stratigraphy within the top $\sim$50 m of the ice rise (Hawley et al., 2014). ~~These two~~ Both radar surveys were collected with snowmobiles moving at 8–10 km h^{-1} towing the antennas. The antenna positions were determined using kinematic GPS attached to the snowmobiles. ~~This~~ The measurements resulted in an average ~~radar trace~~ radar-trace spacing of $\sim$5 m for the deep-sounding radar and $\sim$0.25 m for the shallow-sounding radar.

Post processing included using a dewow filter, an Ormsby band-pass filter, and depth-variable gain functions. To calculate ice thickness, we assumed a radio-wave propagation speed of 169 m μs^{-1} and added a firn correction term of 4–6 meters to account for faster propagation in the firn. ~~We used an optimization inversion routine (Brown and Matsuoka, in prep) to model depth profiles of density along shallow radar profiles using (1) surface densities measured at 13 locations, and (2) depth profile of the density measured along the 23 m long firn core. We then used the~~ The correction was estimated using the modeled depth profiles of the density along the radar profile ~~to estimate laterally variable firn corrections. The magnitudes of the firn correction vary between 4–6 m. To calculate depths of englacial reflectors, we used variable propagation speeds discussed later in Section~~ based on firn-core density observations and shallow-radar data, as further discussed in section 4.1.

3.3 Firn cores and borehole-temperature measurements

~~We~~ To record the stratigraphy (visual, chemical, isotopic, and dielectric), we drilled a 23 m long firn core near the ~~summit of Blåskimen Island and transported the frozen samples to laboratories to develop visual stratigraphy as well as chemical, isotope, and dielectric stratigraphy~~ice-rise summit. The core was dated back to 1996 by counting annual cycles of oxygen isotopes ~~,~~ and by identifying volcanic horizons using non-sea-salt sulphate data (Vega et al., 2016). ~~They found that~~ The resulting SMB in the past 17 years ranges between 0.44 m a^{-1} in 2004 and 1.32 m a^{-1} in ~~2011, giving the mean SMB in this period 0.76 m~~

~~a^{-1}; 700 kg m^{-2} a^{-1} in this paper,~~ 2011. (Throughout this paper, we give mass balance and SMB ~~are always shown~~ as meters of ice equivalent). The values give a mean SMB in this period of 0.76 m a^{-1}.

We installed a thermistor string in the borehole and measured temperature profiles from surface to 20 m depth. Within 25 hours after ~~the completion of drilling , the temperature became steady with~~ drilling finished, temperatures stabilized at each depth within ± 0.1 °C of variation~~at each depth~~. At depths between 8 and 12 m the temperature was ∼ -16.2 °C.

Separately, we drilled nine 3 m long firn cores (~~locations are shown in~~ see Fig. 1b ~~) to measure~~ for locations), then measured their core volumes and weights to determine the spatial variations of surface density. Hereafter~~we call~~, we refer to mean density in the top 3 m as surface density. ~~It was determined by measuring core volume and weight.~~ Measured surface density through firn cores varies by ± ∼2.5% over the ice rise, with a mean value of 453 kg m^{-3} (uncertainty: 3% or 14 kg m^{-3}). However, no distinct pattern in surface density variation was observed in terms of elevation or slope direction. ~~When estimating SMB below, we bilinearly interpolated the surface density~~ We then used the bilinearly interpolated surface density to estimate SMB.

4 Analytical methods

4.1 Surface mass balance

We estimated ~~surface mass balance (SMB) using two different~~ SMB using two methods. The first method uses the heights of GPS stakes above the snow surface. The second method ~~for determining SMB~~ uses isochronous radar reflectors profiled with the shallow-sounding radar. Both methods require surface-density distribution measurements. The stake method is simpler and provides insight on SMB pattern over the ice rise for the period of 2013–2014. The radar method has higher uncertainties, but provides a longer-term view of past SMB patterns.

~~We~~ For the stake method, we estimated SMB at each stake by multiplying the measured stake-height differences by the measured surface density. Considering measurement errors and uncertainty accounting for snow densification (Eisen et al., 2008), this estimate has an overall uncertainty of ± 6%. We ~~consider~~ considered the sinking of the stake under its own weight to be minimal, as the observed surface densities are high.

~~Provided that radar reflectors are isochronous (Richardson et al., 1997), SMB can be derived~~ For the radar method, we derive SMB from dated radar reflectors ~~. In this~~ assuming that radar reflectors are isochronous (Richardson et al., 1997). In our analysis, we ~~assume~~ also assumed that the effects of vertical strain (thinning after the deposition of snow) on reflector depths are negligible so that thickness of an ice layer bounded by the radar reflectors ~~are~~ is solely controlled by the differences in SMB (Waddington et al., 2007). ~~Thus shallow-ice approximation can hold, when~~ With these assumptions, the shallow-layer approximation holds when the depth h (ice equivalent) of a radar reflector is much smaller than the local ice thickness H ($h \ll H$). For our case, h/H is less than 0.04 and thus the ~~shallow-ice~~ shallow-layer approximation is in most cases valid.

However, the ~~shallow-ice~~ shallow-layer approximation may not be valid in areas where vertical strain rates are large, such as in the region near an ice-flow divide, hereafter just "divide" (Gillet-Chaulet et al., 2011; Kingslake et al., 2014). In this region, accumulated effects of variable vertical strain can result in upward arches in isochrones (Fig. 2c), so-called Raymond arches (Raymond, 1983), which ~~were~~ have been found at many other ice rises (e.g. Vaughan et al., 1999; Conway et al., 1999; Nereson and Raymond, 2001). ~~Such~~ Similar upward arches can also be caused by anomalously low SMB near the summit, possibly due to wind erosion (Drews et al., 2013, 2015).

Vaughan et al. (1999) demonstrated that the amplitudes of upward arches induced by anomalous SMB increases linearly with ice-equivalent depth, whereas the Raymond effect makes the amplitude increase quadratically. We used this criterion to diagnose the origin of shallow upward arches near the current summit (Fig. 2b) ~~. We first derived~~ as follows. First, we derived the ice-equivalent ~~depths of~~ depth of the reflectors, assuming that firn density does not vary laterally. For this purpose, we used the depth profile of density $\rho(z)$ at the core site. We estimated local propagation speed $v(z)$ at ~~a~~ depth z using ~~a~~ the relationship between density and refraction index $n(z)$ ~~(Kovacs et al., 1995):~~

$$v(z) = \frac{c}{n(z)} = \frac{c}{1+0.851\rho(z)}$$

~~Here,~~ from Kovacs et al. (1995). Specifically,

$$v(z) = \frac{c}{n(z)} = \frac{c}{1+0.851\rho(z)}, \tag{1}$$

where c is the ~~propagation~~ speed of light in ~~the~~ a vacuum (300 m μs^{-1}). Then, we estimated two-way propagation time $t(z)$ to each depth z:

$$t(z) = \int_{0}^{z} \frac{2}{v(z)} dz. \tag{2}$$

Second, using these ice-equivalent depths z, we measured arch amplitudes from the arch top to the baseline defined with reflector depths 1 km away to both sides of the arch.

~~Under the shallow-ice~~ Under the shallow-layer approximation, we accounted for density variations using two methods. The first method ~~is to account~~ accounts only for vertical variations in density and ~~ignore its~~ ignores any lateral variations. For this purpose, we used the measured densities of the 23 m long core. The second method ~~is to account~~ involves simultaneously inverting for spatial variations in density, temperature, and SMB ~~altogether using an inversion method~~ (Brown and Matsuoka, in prep). It uses an optimization inversion routine to solve for the best fit between a steady state firn density model (Herron and Langway, 1980) and the measured two-way travel times to multiple isochrones identified in shallow-radar profiles. Our optimization routine is constrained by surface densities measured at 13 locations along the shallow-radar profile as well as the measured depth-density profile along the 23 m long firn core.

The former method is not strictly valid, because the surface density varies by ± ∼2.5% and possible variations in SMB add more complexities in density at depths away from the core site. The latter method is also not strictly valid as it solves for the best fit at all locations to a steady-state firn densification model. Firn-core analysis shows no significant temporal trend, but large year-to-year variations by a factor of three over the past 17 years (Vega et al., 2016). Nevertheless, the model fits the measured density well (within 95% confidence bounds of the fit). Although these two methods use distinct assumptions, we ~~show~~ find that they give ~~consistent results and thus~~ similar patterns (e.g., Fig. 2a) and thus provide more confidence in SMB estimates~~using inaccurate data representations in these two methods~~.

4.2 Mass balance of the ice rise

We applied the Input–Output (~~I-O) Method~~ I–O) method (e.g., Rignot and Kanagaratnam, 2006; Conway and Rasmussen, 2009; Zwally and Giovinetto, 2011) to individual columns over the ice rise (Section 4.2.1). The ~~I-O~~ I–O Method calculates the mass balance as a difference between incoming Q_{in} and outgoing Q_{out} fluxes from all the sides of a column, with SMB (M_{SMB}) over the column area added. ~~Here, we ignore basal melting, as~~ As a one-dimensional thermomechanical model (Neumann et al., 2008) shows no basal melt for the ~~geothermal flux estimated~~ geothermal-flux estimate in this region (57 mW m^{-2}; Fox Maule et al., 2005)~~. Radargrams~~, we ignored basal melting. Moreover, radargrams show no anomalous features in the radar reflection from the bed that could indicate basal melting (Fig. 2c).

The ice-flow fluxes through an ice column are calculated as ~~:~~

$$Q = \rho\gamma u_{\perp} h. \tag{3}$$

Here, ρ is the density of a column, and γ is a dimensionless factor ~~which~~ that scales the measured ~~surface flow~~ surface-flow speed $u_{\perp}$ normal to the gate to depth averaged speed $u_{av\perp}$; $u_{av\perp}$ = γ $u_{\perp}$, with $\gamma \leq$1. ~~This implicitly assumes~~ The relation requires that ice-flow direction does not change with depth, which seems valid over relatively flat bed terrain underneath the ice rise (Section 5.1).

4.2.1 Constraining γ

The parameter γ is a function of local surface slope, ice thickness, ice temperature and ice rheology (Cuffey and Paterson, 2010). ~~For~~ Assuming isothermal ice flow over a non-sliding bed and ~~assuming~~ using the shallow-ice approximation, γ ~~can be stated as γ~~ = $\frac{(n+1)}{(n+2)}$, where n is the creep exponent of Glen's flow law (Cuffey and Paterson, 2010, p.310). Previous studies on ~~ice-flow divides~~ divide flow suggest that n ~~can be~~ lies between 3 and 5 (Martín et al., 2009a, b; Gillet-Chaulet et al., 2011; Drews et al., 2015)~~. Then~~, giving a γ ~~ranges between 0.8~~ between 0.80 (n = 3) ~~,~~ and 0.86 (n = 5).

~~The actual range of~~ However, due to ice-temperature variations and ice-divide effects, the latter of which invalidate the shallow-ice approximation, the range of γ ~~can be different, because the isothermal approximation is hardly valid. Also, near the ice-flow divide the shallow-ice approximationis invalid as longitudinal stresses are significant (Raymond, 1983).~~

should be wider. For example, Reeh (1988) showed that ~~, near the flow~~ near the divide, γ can be close to 0.5 ~~,~~ when n = 3 and ice is isothermal. ~~As~~ But, as ice becomes warmer at greater depths, the deeper ice is presumably softer than the shallower ice, implying that γ is larger~~when ice-temperature variations are considered~~. Hence, it is reasonable to assume that $0.5 \leq \gamma \leq 1$. Raymond (1983) used an isothermal model, and Hvidberg (1996) used a thermomechanical model to constrain the range of γ near the divide. Both showed that γ ~~is smallest at the divide, and varies largely near the divideregion~~varies the most near the divide, being smallest right at the divide.

~~Out~~ Outside of the divide region by several ice thicknesses ~~from the divide~~H or more, γ becomes less variable. For isothermal two-dimensional (divide) flow within 8H of the divide, $0.61 \leq \gamma \leq 0.75$ ~~(< 8~~(Raymond, 1983) and within 10H ~~from~~ of the divide, ~~Raymond (1983)) and~~ $0.56 \leq \gamma \leq 0.77$ ~~(<~~(Hvidberg, 1996). Also within 10H ~~from~~ of the divide, ~~Hvidberg (1996)). For~~

~~themo-mechanical case ,~~ the case of thermomechanical flow gives $0.69 \leq \gamma \leq 0.86$ ~~($< 10H$ from the divide, Hvidberg (1996)) and for~~ (Hvidberg, 1996) and the case of isothermal axisymmetric radial flow gives $0.54 \leq \gamma \leq 0.76$ ~~($< 10H$ from the divide, Hvidberg (1996))~~(Hvidberg, 1996). Although radial flow leads to ~~an increase in the~~ a larger divide region, $\sim$ 70% of the changes in γ still happen within 4~~ice thiknesses from~~ H of the divide. Therefore, for the setups discussed below (with an average extent of $\sim$9 km or 18 ice thicknesses from the divide), γ remains ~~virtually~~ effectively uniform.

In ~~the study, we consider the~~ each estimate below, we assume a spatially uniform γ~~in each estimate ,~~ , and examine ensemble results ~~for~~ within the plausible range ~~(~~of 0.7–0.9~~). More~~ . As ice rheology has a memory through ice temperature and crystal fabric, a more accurate determination of γ requires ~~the~~ knowledge of ice-rise evolution in ~~the past millennia, because ice rheology has a memory through ice temperature and crystal fabric. This~~ past millennia. Such knowledge requires detailed ice-flow modelling, which is beyond the scope of this study.

4.2.2 Estimate setups

~~We estimated~~ Here we estimate mass balance for three ~~different~~ setups: (i) several flowbands along GPS stakes and radar profiles, (ii) polygons bounded by GPS stakes, ~~(ii~~and (iii) uniformly-distributed square columns (grid) on the ice rise~~and average them~~ . For ii), values are averaged over individual polygons~~for (i), and (iii) several flowbands along GPS stakes and radar profiles~~. The flowband setup relies more on direct field measurements, but has very limited spatial coverage. The polygon and grid setups have good spatial coverages, but they ~~require data interpolationsto large degrees. The flowband setup relies more on direct field measurements, but has very limited spatial coverage. Therefore, we use these three mass balance estimates as an ensemble~~rely upon data interpolations. Because it is difficult to accurately determine the net uncertainties associated with such data interpolations, we used two setups (polygon and grid) with distinct data interpolations and consider the resulting difference between them as an estimate of these net uncertainties.

4.2.2.1 Flowband setup

In this method, we calculated mass balance along ice-flow bands of varying widths along three slopes of the ice rise. We define a flowband width to account for flow divergence and convergence along the flowband, assuming that ice flows along the steepest-descent path on the surface. Flowband width at the downslope end is taken as 1 km, and for each flowband, the steepest-ascent paths are determined from two points 0.5 km away from the most downstream GPS stake. We used ascent path instead of descent because the surface topography near the summit is much less distinct and consequently the divergence estimate is more sensitive to small topographic changes. We rejected three flow profiles out of six because the GPS markers were not within the defined flowband. Along the remaining three flowbands, their widths vary by a factor of 1.4–3.6. This variation depends on the initial band width (1 km used here), but over the range of the initial band width between 0.9 and 2.5 km, the band width estimates vary only $\sim$3%. We further divided the flowbands into three columns based on the available data and calculated mass balance as per the I-O method.

4.2.2.2 Polygon setup

As ice rises are expected to show ~~slope dependent~~ slope-dependent SMB features (King, 2004; Lenaerts et al., 2014), it is probable that mass balance could also have similar features. To account for ~~this, in this method we divide~~ a possible slope dependence, this setup involved dividing the ice rise into 19 polygons ~~in~~ with respect to the surface slope direction and data availability. All ~~four~~ sides of these polygons act as a flux gate. Ice thickness and surface-flow velocities are available at each corner of these polygons. We ~~observe some cases that ice is~~ observed some cases in which ice was thicker at one corner~~but ice flows~~ , but the flow was faster at the other corner. ~~Therefore, to better account for these variations along the~~ To address such variations along a flux gate, we divided each gate into ten subgates and estimated the flux at each subgate, rather than calculating mass flux using single values averaged over an entire gate.

4.2.2.3 Grid setup

~~We divide~~ This setup involves dividing the ice rise into a grid with 200 m long square columns and ~~estimated~~ estimating mass balance for each column. The ~~mass balance~~ mass-balance values are then averaged over each polygon ~~used in the~~ of the above polygon setup. ~~We adopt this setup, together with the polygon setup, to~~ By comparing these two setups, we can test how data interpolations affect the ~~mass balance~~ mass-balance estimate. We ~~calculated~~ calculate mass balance MB ~~using~~ by calculating the continuity equation to each grid element ~~:~~ as

$$MB = \frac{\partial h}{\partial t} = M_{SMB} + (\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y})H + (u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y}), \tag{4}$$

~~Where~~ where u and v are the components of ice-flow vectors in the rectangular (local coordinate) directions x and y, and h is the variable for ice thickness. We bilinearly ~~interpolate~~ interpolated the measured u, v, M_{SMB}, and H into grids.

4.2.2.4 ~~Flowband setup~~

~~In this method, we calculate mass balance along ice-flow bands of varying widths in three different slopes of the ice rise. We define a flowband width to account for flow divergence and convergence along the flowband, assuming that ice flows along the steepest descent path on the surface. Flowband width at the downslope end is taken as 1 km, and for each flowband, steepest ascent paths are determined from two points 0.5 km away from the most downstream GPS stake. We used ascent because the surface topography near the summit is much less distinct and consequently the divergence estimate is more sensitive to small topographic changes. We rejected three flow profiles out of six, because the GPS markers were not within the defined flowband. Along the three flowbands, the flowband widths vary by a factor of 1.4–3.6. This variation depends on the initial band width (1 km used here), but over the range of the initial band width between 0.9 and 2.5 km, the band width estimates vary only ~3%. We further divided the flowbands into three columns based on the available data and calculated mass balance similarly to the polygon setup.~~

5 Results

5.1 Topography and surface-flow ~~field~~velocity

Figure 3a shows surface elevations derived from kinematic GPS surveys using bilinear interpolation. The summit is 410 m a.s.l. and is $\sim$350 m higher than the surface of the ice shelf on the southern side (ice-shelf elevation is taken from Fretwell et al. (2013)). From the summit, the elevation drops gradually towards the edges of our survey region in all directions, giving a ~~relatively dome-shaped topography~~ dome-like shape to the ice rise. A pronounced ridge extends from the summit to the southwest. The eastern flank shows locally steep slopes and a basin in ~~northeast with~~ the northeast with an overall lower, less-tilted surface. The eastern steep slopes and the southwest ridge are consistent with lineations observed in satellite imagery (light gray feature over dark gray in Fig. 1b). Along a profile through the summit (2–2' in Fig. 1b), the absolute surface slope smoothed over 500 m long segments ranges between 0.02 and 0.04, except for the ~~summit vicinity of~~ region within $\sim$~~1 km~~ 0.5 km of the summit where the surface is virtually flat (Fig. 2a).

~~The radar profiles visualized the bed as well as ice stratigraphy (Figs.2b and~~ From the radar profiles (e.g., Fig. 2c)~~. The measured ice thickness of Blåskimen Island~~, we located the bed to determine the ice thickness. The resulting thickness ranges between 374 m (first quartile) and 444 m (third quartile), with a mean value of 400 m. The ice becomes thinner gradually in all directions away from the summit. Considering uncertainty associated with digitization of the bed reflector, data sampling, and firn correction, the uncertainty in the ice thickness is ± 5 m.

~~We derived the bed elevations by subtracting the ice thicknesses from the surface elevations~~The bed elevation here equals the surface elevation minus the ice thickness. At locations where radar data are available, the bed elevation is on average 110 m below the current sea level (i.e., -110 m a.s.l.), ranging between -68 m a.s.l. and -125 m a.s.l. (first and third quartiles, respectively). The highest point (-22 m a.s.l.) on the bed ~~was observed~~ occurs about 6 km northeast of the summit (along the 4–4' profile, see Fig. 1b). We developed a bed DEM using bilinear interpolation (Fig. 3b). The bed of the central part of ice rise is very flat; in this region, bed elevations vary only by $\sim$50 m within an area of $\sim$100 km^2. Also, individual radar profiles show that this region is smooth (Fig. 2c). This low, flat, and smooth region extends from the summit vicinity towards north and northwest, and constitutes the majority of the ice-rise bed. However, towards the southern end of the survey domain, the bed elevation decreases by $\sim$200 m over a horizontal range of $\sim$5 km, resulting in a mean bed slope of $\sim$0.04. Another steep bed region (0.03–0.04) ~~is found~~ occurs in the northeastern slope. These steeper regions in the bed are associated with steeper regions on the surface, although the surface is not as steep as the bed.

The surface-flow ~~field is~~ velocity measurements are shown in Fig. 3c. The GPS stakes within 2 km of the summit moved only negligibly ($<$ 0.1 m a^{-1}). The displacement of stakes outside the summit region is larger and increases downstream; ice flows less than 3 m a^{-1} within 4 km ~~from~~ of the summit and 10–15 m a^{-1} downslope. Ice flows slowest along the ridge towards the southwest, whereas the fastest flow is along the south section of flowline 2–2'. The estimated positions have a mean precision of 4.9 cm and 5.1 cm for the east/west and north/south components leading to a processing uncertainty on the velocity of ± 7 cm a^{-1}. This does not include uncertainty associated with any tilt of the stakes. Nevertheless, as the velocities outside the summit area range between 4 m a^{-1} and 15 m a^{-1}, and the observed tilts were small, we ~~consider~~ considered this uncertainty to be negligible.

5.2 Surface mass balance

The mean SMB from 90 stake-height measurements across Blåskimen Island is 0.78 m a^{-1}, for the period between January 2013 and January 2014 (Fig. 4a). SMB varies by a factor of 3.3 over the study area ~~of ∼20 km by ∼20 km~~ (0.28–1.03 m a^{-1}), with 80% of the values ranging between 0.69 and 1.03 m a^{-1}. The SMB shows a distinct spatial pattern~~; it is~~ : larger in the ~~southern~~ southeastern slope and smaller in the ~~northern~~ northeastern slope. The surface is rougher ~~(sastrugi)~~ due to sastrugi in the low SMB region~~whereas~~ , but smoother and softer in the high SMB region, indicating strong ~~impact~~ influence of the wind. The summit vicinity has a large number of stakes ~~, which~~ that show small variations of SMB, but without any distinct pattern.

The shallow-sounding radar visualizes continuous reflectors within the firn (Fig. 2b). No major disruptions are observed that can be associated with surface melt or strong wind scour. Therefore, we assume these continuous reflectors are isochrones (Richardson et al., 1997). With this assumption, we can associate firn-core ages to radar reflectors. We tracked three such reflectors to almost the full extent of the radar surveys; at the 23 m long core site, they are at 8.4 m ~~(actual depth~~ depth (or 2.15 m ice-equivalent depth; dated 2011 or 3 years before the survey by Vega et al. (2016)), 11.9 m (4.2 m; 2009), and 12.8 m (6.9 m; 2005).

To judge whether the reflector depths are controlled primarily by SMB or the Raymond effect (Section 4.1), we measured the amplitudes of arches near the current ~~ice-flow divide. This analysis was made for~~ divide. Due to the shallowest reflector having insignificant amplitude, we used just the two deeper reflectors of ~~three that we~~ the three that were used for SMB estimates~~, as the arch amplitude for the shallowest reflector is insignificant~~. In addition, we measured arch amplitudes of six more reflectors at greater depths. These reflectors range between ∼4 m and ∼35 m ice-equivalent depth (Fig. 2b). We analyzed the arch amplitudes in this depth range to ~~better~~ resolve their depth variations. All four radar profiles across the summit (Fig. 1b) show that the arch amplitude increases linearly with depth (Fig. 5). Therefore, we conclude that the ~~shallow-ice~~ shallow-layer approximation can be used all along the radar profiles, and thus the three radar reflectors within the top ∼7 m ice-equivalent ~~represents~~ represent spatial patterns of SMB.

The 23 m long core shows that the density varies ∼36% (450–655 kg m^{-3}) vertically along its length and the 13 shallow cores show that the surface density varies ± ∼2.5% horizontally. Amongst three reflectors we ~~analysed~~analyzed, the deepest reflector (12.8 m actual depth at the core site) has the largest depth range between ∼8 and ∼15 m. ~~It implies that the use of a uniform density could~~ Thus, to make the SMB estimates ~~less accurate, and variable density should be accounted for~~ more accurate, one should account for variable density.

Figure 2a shows the SMB averaged over the past 9 years (2005–2014) estimated using the two radar methods along the profile 2–2’. ~~The differences between the SMB estimated with these two methods are localized to the region in 1–6 km north (profile2–2’,~~ This profile, as well as the other profiles (not shown in Fig. 2a) ~~and northeast (~~ show that the first estimate (accounting for the vertical density variations only) usually exceeds the second estimate (accounting for both lateral and vertical density variations) by about 5–10%. The largest difference (0.16 m a^{-1}) was found in the region 1–6 km northeast of the summit along profile 4–4'~~) of the summit~~. Except for this region, these two methods give nearly identical SMB spatial patterns along the radar profiles. Figure 4b shows the SMB estimated using the first radar method~~(accounting for the vertical density variations only)~~. It gives the spatially mean value of 0.81 m a^{-1}, with the first and third quartiles of 0.71 and 0.93 m a^{-1} respectively. The second radar method ~~accounting for both lateral and vertical density variations gives a slightly lower number than the second radar method by 5–10%; the mean value for the second radar method is~~ has a mean value of 0.75 m a^{-1}, with first and third quartiles of 0.65 and 0.85 m a^{-1} respectively.

~~Factors determining the uncertainty~~ Consider the uncertainties in SMB derived from dated radar isochrones~~can be broadly categorized as:~~. In broad categories, these arise from errors in (1) ~~error in~~ determining the depth of the reflector, (2) ~~error in~~ dating the firn core, and (3) ~~error in~~ estimating the cumulative mass above the reflector and its spatial variability. For the first source~~we assess~~, we estimate the uncertainty to be within ± 10 cm. ~~We consider~~ For the combined errors in depth-age scale and error in linking it to radar reflector, we estimate this to be ± 1 year. ~~The~~ Finally, the density model used to fit the observations has an uncertainty of ± 3%, whereas we see ± 3% variability in the surface density. Using standard error propagation, this results in an uncertainty of ± 11%~~. It is larger than an~~, a value that exceeds the uncertainty of ± 6% for the stake method.

5.3 Mass balance

We estimated mass balance over the nine-year period between 2005 and 2014 (Fig. 6)~~. The~~, using the SMB estimate over this period. For other inputs to the estimate, we assumed that the present observations are representative of this period. For the mean value, the flowband setup shows a mean mass balance of +0.12 ± 0.10 and +0.27 ± 0.10 m a^{-1} over the range of γ. The uncertainty (± 0.10 m a^{-1}) is estimated using the uncertainties in ice thickness (± 5 m), flow speed (± 7 cm a^{-1}), ice density after correcting for firn (± 2%), and SMB (± 11%) with propagation of errors.

The polygon and grid setups give very similar spatial patterns to each other. For these two setups, ~~in addition to the measurements errors above, the mass balance estimate is largely~~ the mass-balance estimate is also affected by errors associated with data ~~interpolations~~interpolation. Because it is difficult to ~~accurately determine the net uncertainties associated with data interpolations~~determine these errors accurately, we used two setups (polygon and grid) with distinct data interpolations and consider the differences between them as ~~a guide of representative~~ an estimate of uncertainties associated with the data ~~interpolations.~~

interpolation. We averaged mean ~~mass balance~~ mass-balance values of all ice columns for each setup and for each γ~~(shown with point symbols in Fig.~~. Figure 7 ~~). For~~ shows that, for a given γ, the polygon setup ~~give~~ gives the largest estimate, whereas the grid-setup estimate is smaller by 0.02~~-~~–0.03 m a^{-1}. Because this difference is smaller than the uncertainty for the flowband-setup estimate (± 0.1 m a^{-1}), ~~we argue that the interpolation errors are not dominating~~ interpolation errors probably do not dominate these results. Higher γ values correspond to lower mass balance, and the sensitivity of mass balance to γ is nearly uniform for individual columns.

~~All the polygons~~ For polygon and grid setups, all the columns show positive mass balance over the full γ range, except for ~~southernmost~~ southeasternmost downstream polygon A3 (the slope-direction codes are shown in Fig. ~~6a~~6b). Along slopes C, E and F, mass balance ~~increases monotonically downstream~~does not vary significantly along the slope, whereas mass balance of polygons along slopes A, B~~and D slopes~~ , and D is more variable. ~~Adjacent southern slopes A and F show contrasting features; the slope A shows the least thickening, whereas the slope F shows the most thickening.~~ For the flowband setup, ~~one column~~ six of nine columns show positive mass balance, with columns CD3 and DE1 (see Fig. 6a for the slope-direction codes) being very close to balance. Column DE3 has negative mass balance in the northwest downstream, a region where the estimated flow divergence is anomalously large.

~~In conclusion, overall,~~ In summary, the measurements show that Blåskimen Island ~~has~~ had positive mass balance ~~in the past nine years.~~ between 2005 and 2014. Thickening rates vary depending on the setups and the choice of γ. Over the range of γ used here ($0.7 \leq \gamma \leq 0.9$), the mean mass balance varies between +~~0.25~~ 0.12 ± 0.10 and +~~0.37~~ 0.27 ± 0.10 m a^{-1} for the ~~polygon~~ flowband setup, between +~~0.21~~ 0.25 and +~~0.35~~ 0.37 m a^{-1} for the ~~grid~~ polygon setup, and between +~~0.12 ± 0.10~~ 0.21 and +~~0.27 ± 0.10~~ 0.35 m a^{-1} for the ~~flowband~~ grid setup. Outside the divide region, ~~gamma tend~~ γ tends to be higher (0.8–0.9; Section 4.2); consequently, the thickening rates lean towards the lower end of the estimate above.

6 Discussion

6.1 Topographic characteristics

According to a recent inventory of ice rises and rumples in Antarctica (Moholdt and Matsuoka, 2015; Matsuoka et al., 2015), Blåskimen Island (651 km^2) ~~is larger~~ has greater areal extent than 91% of isle-type ice rises (mean: 151 km^2). Its summit is 410 m a.s.l., which is higher than 89% of the others (mean: 168 m a.s.l.). Maximum measured ~~ice flow~~ ice-flow speed (15 m a^{-1}) is ~~above the mean of maximum ice flow speed~~ larger than the mean value for the other isle-type ice rises (13 m a^{-1})~~for isle-type ice rises~~. Also, the mean bed elevation at -110 m a.s.l. is higher than 86% of the others (-178 m a.s.l.). Overall, Blåskimen Island is one of the larger isle-type ice rises.

~~Detailed surface DEM developed with the kinematic GPS survey~~ Our detailed surface DEM (Fig. 3a) ~~revealed many distinct topographic features including the southwestern ridge and steep slopes in the east. In addition, it confirms that lineations in satellite imagery are associated with surface undulations (Goodwin and Vaughan, 1995). The lineations appear where the surface slope varies largely and most of them are associated with uneven bed topography. This supports the use of satellite imagery as a mean to explore first-order surface and bed topography, when an ice rise remains un-surveyed.~~

~~Distinct topographic features of the ice surface revealed with our DEM are not fully represented~~ reveals a number of surface topographic features that are smoothed over in continent-wide DEMs~~(e.g. Bamber et al., 2009; Fretwell et al., 2013, in which spatial resolu~~ ~~Also, the summit heights in those products are 24–40 m lower than our measurements. It remains unclear how much this inaccurate description of topography affects modeling~~ . For example, two widely-used DEMs (Bamber et al., 2009; Fretwell et al., 2013) sh different topography of the ice rise and elevations are off from our local DEM by 10-100 m at different places. Ice rises have much steeper slopes than the continental slope (Fig. 2a), which inherently requires high-spatial resolutions to represent the topography accurately. This missing detail could affect modelling SMB and surface density. Lenaerts et al. (2014) demonstrated that elevated topography associated with ~~ice rises causes orographic precipitations and corresponding~~ an ice rise causes orographic precipitation and the resulting precipitation shadow not only over ~~ice rises~~ the ice rise, but also on the adjacent ice shelves. Such variations could result in anomalous ~~firn density~~ firn-density estimates over the ice shelves, which would result in ill-posed estimates of freeboard thickness and ~~its~~ the resulting long-term changes of adjacent ice shelves.

Our local DEM confirmed that lineations in satellite imagery over Blåskimen Island appear where the surface slope has greater variability, with most lineations being associated with uneven bed topography. Such an association was originally proposed over Fletcher Promontory Ice Rise by Goodwin and Vaughan (1995). This agreement supports the use of satellite imagery as a remote means to explore first-order surface and bed topography.

6.2 Surface mass balance

We found good agreement in the spatial patterns of stake-measured SMB between 2013 and 2014, and radar-measured SMB between 2005 and 2014 (Figs. 4a and 4b). Relative thicknesses of three layers bounded by radar isochrones (and the surface) vary similarly along the profiles (Fig. 2b), ~~inferring~~ from which we infer that spatial patterns of SMB have remained ~~similar over this~~ relatively constant over the 9 year period ~~,~~ 2005–2014. SMB averaged over this period ~~vary largely~~ has a mean of 0.81 m a^{-1}, but varies along the radar profiles between 0.71 m a^{-1} (first quartile) and 0.93 m a^{-1} (third quartile)~~, with its mean of 0.81 m a^{-1}~~.

~~Large~~ Such large spatial variability in SMB ~~was found on other ice rises as well.~~ has been observed on other Antarctic ice rises. For example, King (2004) showed that SMB on ~~the~~ Lydden Ice Rise, Brunt Ice Shelf, is highly variable both at large (tens of kilometers) and small spatial scales (hundreds of meters). They demonstrated that large-scale variations are a result of orographic precipitation, whereas small-scale variations are a result of snow redistribution. On both scales, the contribution from sublimation was ~~found to be~~ relatively small. They ~~highlighted~~ emphasize that SMB is sensitive to surface topography~~;~~, with small variations in surface topography ~~cause~~ causing small changes in wind speed, which ~~could result in~~ can cause large SMB variations ~~,~~ due to the nonlinear relationship between wind speed and snow transport. On Blåskimen Island, we compared the SMB values to local surface slope measured along the kinematic/radar profiles. Although we found no clear relationship between them, we did not sample along the prevailing wind direction, where the effect would be strongest.

~~Net~~ The net impact of these mechanisms on SMB in the DML coast ~~was examined using~~ has been examined using the RACMO2 regional climate model (Lenaerts et al., 2014). Among all the ice rises included in their study, SMB varies by a factor of 2–~~6 between ice rises.~~ 6. On Blåskimen Island, we found that upwind slopes have 2–3 times the SMB ~~on~~ than the downwind slopes, which is within the model prediction (2–4 times; Lenaerts et al. (2014)). Similar SMB gradients are found over other ice rises in DML: 2–3 times over ~~the~~ Halvfarryggen Ice Dome (Drews et al., 2013) and about 2 times over the Derwael Ice Rise (Drews et al., 2015). We ~~compared the SMB values to local maximum surface slope (not necessarily along the prevailing wind direction) but found no clear relationship between them. We~~ observed numerous sastrugi and harder snow on the northwestern downwind slopes, a clear indication of snow erosion~~/~~–redistribution processes. Another feature ~~is found~~ occurs near the summit, where the surface is virtually flat; here, SMB is lowered by ~~-~~ ∼10% over ~~-~~ ∼0.5 km. Similar low SMB near the summit has been observed in the Halvfarryggen Ice Dome and the Derwael Ice Rise~~as well, which were~~, where it was attributed to wind erosion (Drews et al., 2013, 2015).

6.3 Present-day mass balance

Amongst all factors that affect the mass balance, the ice-flow speed varies most widely about its mean value (57%), as compared to ~~changes in~~ that for SMB (17%) and ice thickness (11%)~~about their mean values~~. Consequently, the mass balance distribution is more sensitive to the flow-speed distribution than the other factors. This also explains the low mass balance in the A slope (Fig. ~~6). Downstream~~ 6b). The downstream region of the A slope has a lower bed than the central flat basin. As the ice surface is steeper, ice flows faster in this region. Overall, despite the large upwind~~/~~–downwind contrast in SMB (Fig. 4), differential mass flux compensates for the difference in SMB so that no distinct mass balance patterns ~~were found~~ occur (Fig. 6). Our mass balance estimates show that Blåskimen Island is thickening almost everywhere, but the thickening rate is smaller near the summit than the flank. If this pattern ~~is persistent~~ persists for a long period, ~~it would result in flattening of~~ the ice rise ~~initially~~would initially flatten. But ice-flow ~~fields would probably be adjusted~~ velocities would probably adjust to the new topography, ~~so~~ making the net impact of the ongoing differential thickening on ice topography ~~remains unknown~~difficult to predict.

6.4 Long-term evolution~~and impact on the adjacent ice shelves~~

Distinct upward arches in the ice stratigraphy up to ∼40 m depth are caused by low SMB near the summit. We observed upward arches below this depth (Fig. 2c), which are most likely Raymond arches~~, and are conducting ice-flow modelling experiments to interpret them~~. Regardless of its cause, the upward arch locations can be a proxy of the summit position in the past (Nereson et al., 1998).

~~Since~~ The vertical alignment of the arches in the top ∼40 m ~~are aligned vertically~~ below the summit (Fig. 2b) ~~, it~~ indicates that the summit position has been stable over the past several decades. In contrast, the deeper arches (∼300 m a.s.l. and below) show more offset towards the southeast ~~as it goes deeper~~ with increasing depth (radar profile 2–2' shown in Fig. 2c). This trend ~~is also found~~ also occurs in other radar profiles. ~~A possible interpretation of this arch inclination is~~ This arch inclination may mean that the summit has migrated towards northwest in the past. ~~We do not see~~ Present-day results show no clear signs of ~~present-day~~ mass imbalance implying such a divide migration (Fig. 6). ~~It~~ This may indicate recent changes in mass balance and/or, it may indicate a limitation of our mass balance estimate due to a ~~coarse~~ resolution (thousands of meters) ~~, compared to~~ that is coarser than the observed arch offset (100–400 m).

If the upward arches at greater depths are indeed Raymond arches, ~~it indicates that the~~ then the current summit position has likely been stable within several ice thicknesses ~~from the current summit~~ over one characteristic time T ($= H/SMB$, ∼610 years at Blåskimen Island) or longer. If the summit position stays stable for longer time, then ~~Raymond arches are further developed~~ the Raymond arches would further develop into double-peaked arches (Martín et al., 2009a), which are not clearly observed here~~(~~. (We do find a small side arch, but this is caused by a bed bump nearby ~~,~~according to our initial ice-flow modeling~~).~~.) According to Martín et al. (2009a), the double-peaked arches appear after several T, ~~though its mature shape is reached~~ but reach a mature shape only after ∼$10T$ or so. Therefore, we speculate that the summit of Blåskimen Island has been stable within several kilometers at least in the past ∼600 years but no longer than several millennia.

~~Roles of ice rises vary largely in terms of its settings, and thus can change during the evolution (Matsuoka et al., 2015). Blåskimen Island is currently situated at the calving front of the local ice shelves and in the ice-flow shadow of Novyy Island ice rise upstream (Fig. 1). This setting implies that currently Blåskimen Island alone has limited impact on the continental grounding line and ice flux from the ice sheet. However, it seems likely that Blåskimen Island plays a more significant role than the Novyy Island to maintain the current calving front position. Favier and Pattyn (2015) demonstrated that an ice shelf landward of the ice rise is thicker than the seaward ice shelf facilitating formation of rifts and ice-shelf breakups just seaward of the ice rise. To explore the dynamics of this surrounding region better we will use the datasets presented in this study to model the evolution of the ice rise.~~

7 Conclusions

~~Ice rises are a useful resource to investigate evolution and past climate of the DML coastal region. We investigate~~ We used geophysical methods to investigate Blåskimen Island~~ice rise~~, one of the larger isle-type ice rises at the calving front ~~of~~ at the intersection of Fimbul and Jelbart Ice Shelves ~~, using geophysical methods. It has an overall dome shape and at its summit it is~~ on the Dronning Maud Land coast. The ice rise was found to be dome shaped with a summit at ~350 m above the adjacent ice shelf. It stands over a flat bed with a mean elevation of 110 m below ~~the~~ sea level. The ice flows from the summit towards the flank with speeds up to 15 m a^{-1}. We found ~~a~~ good agreement in the spatial patterns of stake-measured ~~Surface Mass Balance (SMB)~~ surface mass balance between 2013 and 2014, and radar-measured ~~SMB~~ surface mass balance between 2005 and 2014. Both ~~show higher SMB~~ showed higher surface mass balance on the upwind ~~slopes~~ slope (southeast) ~~, in comparison to~~ than that on downwind slope (northwest) by ~37%. This variation ~~is~~ was likely a result of orographic precipitation during storms. Using the Input-Output method for a range of parameters and column setups, we ~~conclude~~ concluded that Blåskimen Island has been thickening over the past decade. Thickening rates ~~cannot~~ could not be determined precisely, but ensemble results ~~show that~~ showed that the thickening rate averaged over the ice rise ~~can~~ may be between 0.12 ~~m a^{-1}~~ and 0.37 m a^{-1}. On longer timescales, we ~~speculate~~ speculated that the summit of ~~Blåskimen Island~~ the ice rise has been stable within several kilometers at least in the past ~600 years, but no longer than several millennia.

8 Data availability

Field data (GPR, GPS, borehole thermistor data) and the derived datasets (ice thickness, ~~flow speed~~surface flow velocity, and surface mass balance) will be released at ~~:~~ http://data.npolar.no on the completion of the review process. They are available for the editor and reviewers upon request. The 23 m long firn-core data and their availability are described in Vega et al. (2016).

Author contributions. Matsuoka and Brown designed the study. All three authors conducted fieldwork. Goel led the overall data analysis and interpretations. Brown prepared the GPS and GPR processing workflow, which Goel adapted. Brown also produced inversion SMB estimates. Goel and Matsuoka prepared the manuscript, and Brown contributed to finalize it.

Competing interests. Author KM is a member of the editorial board of the journal.

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Figures

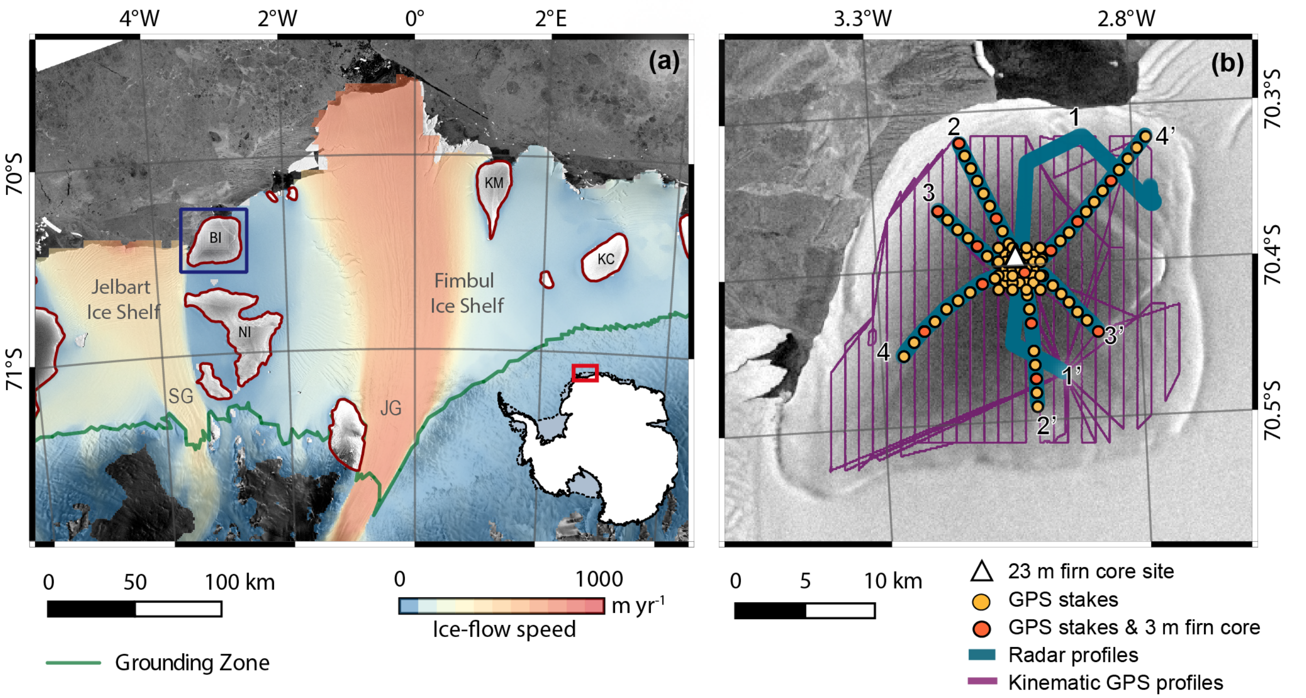

Figure 1. Blåskimen Island~~ice rise~~, Western DML. (a) Blaskimen Island (~~squared~~"BI" in blue square) located between the Fimbul and ~~Jelvart~~ Jelbart ice shelves. Inset shows the coverage of this map. Ice rises are outlined in red (Moholdt and Matsuoka, 2015), and the grounding zone of the ice sheet is illustrated in green (Bindschadler et al., 2011). ~~Color~~ The color scale shows flow speed of the ice sheet and ice shelf (Rignot et al., 2011). The background of ~~the~~ both panels is Radarsat-1 satellite imagery (Jezek et al., 2002). Acronyms stand for BI: Blåskimen Island, JG: Jutulstraumen Glacier, KM: Kupol Moskovskij, KC: Kupol Ciolkovskogo~~and~~ , NI: Novyy Island~~.~~ , and SG: Schytt Glacier (b) Close-up view of Blåskimen Island. Pink curves show kinematic GPS profiles used to determine the surface topography and green curves show radar profiles. Yellow circles show GPS stake positions for ice-flow measurements. Red circles show GPS stake ~~position~~ positions where a 3 m long firn core was also drilled. The white triangle shows the location where the 23 m long firn core was drilled. Maps are projected to the Antarctic Polar Stereographic view (EPSG3031).

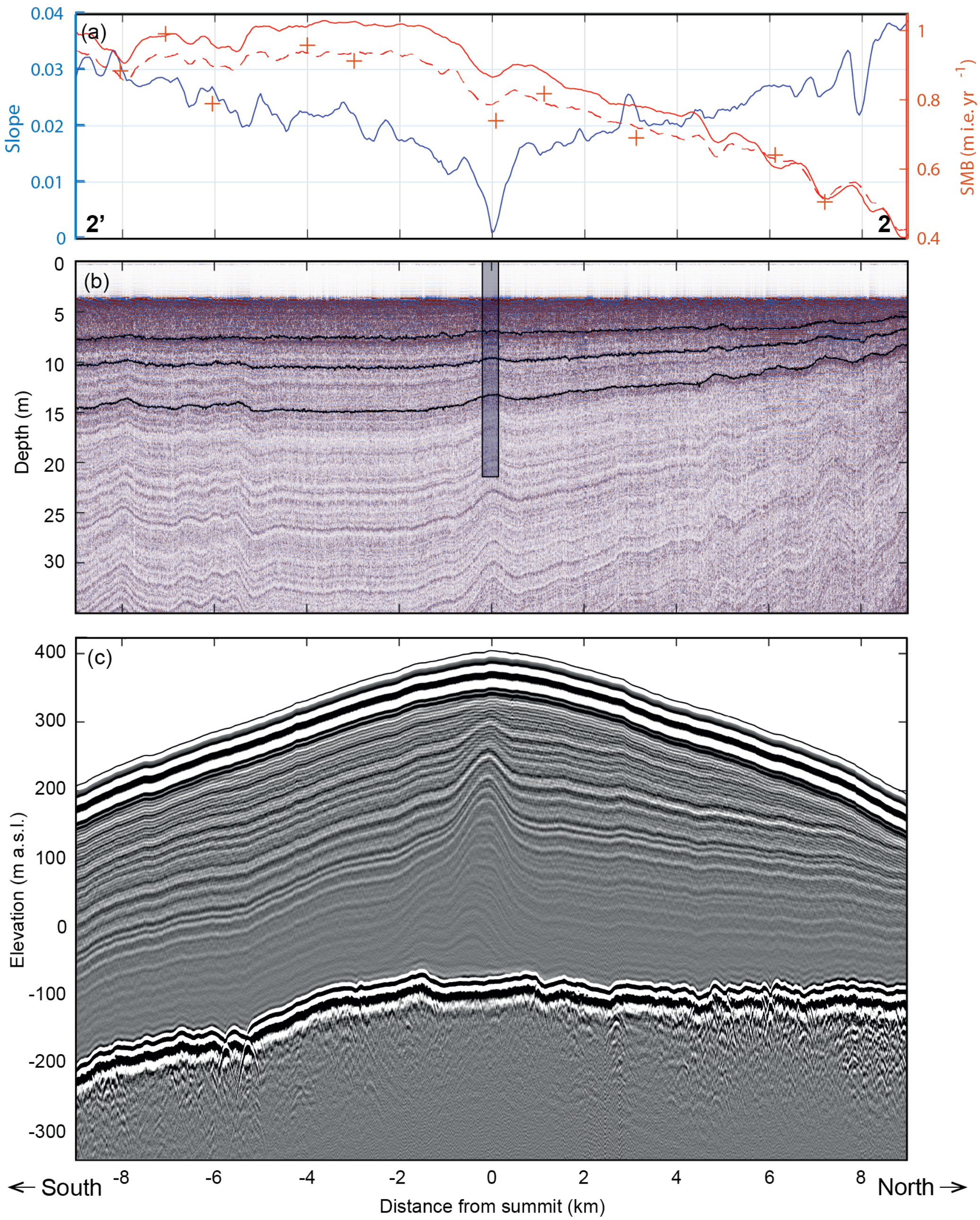

Figure 2. Cross sections of the ice rise along the flowline 2–2' (Fig. 1b). (a) Surface slope (500 m running mean, absolute number, left axis) and SMB (right axis). '+' markers show SMB derived from stake heights. Red curves show the two SMB estimates derived from radar data, with the solid curve assuming only vertical variability in density ~~,~~ and the dashed curve accounting for both vertical and lateral variability in density. (b) 400-MHz radargram. Three englacial reflectors are highlighted, which are dated with the 23 m long firn core (vertical bar) and used to determine SMB. (c) 2-MHz radargram. Data are shifted using the GPS-measured surface elevations to show the topography.

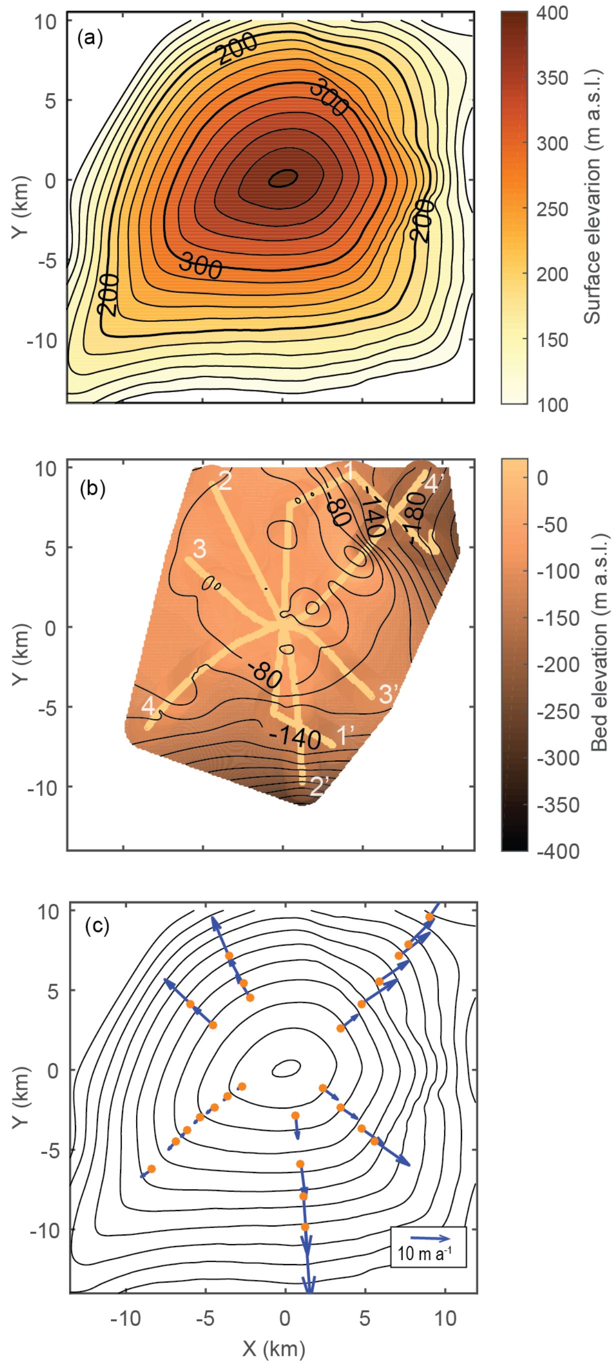

Figure 3. ~~Ice surface (a), bed~~ Ice-rise topography ~~(b)~~ and ~~ice-flow field (c) of the ice rise~~flow velocities. The local coordinates are parallel to the polar stereographic coordinates EPSG3031 and centered at the ice-rise summit. (a~~, b~~) ~~Elevation contours~~ Surface elevation. Contour intervals are 20 m~~intervals~~. ~~In panel~~ (b) Bed elevation, ~~radar~~ also with 20 m contour intervals. Radar profiles used to derive the bed topography are highlighted in yellow to show the data availability. ~~Kinematic GPS survey locations are shown in Fig. 1b.~~ (c) Ice-flow velocities. Surface ice-flow velocities (blue arrows originated from orange circles) overlaid on surface topography (30 m ~~interval contours~~contour intervals). ~~There~~ Kinematic GPS survey locations are ~~more~~ shown in Fig. 1b. GPS stakes near the summit ~~(Fig. 1b), which~~ did not give significant results and thus are not shown here.

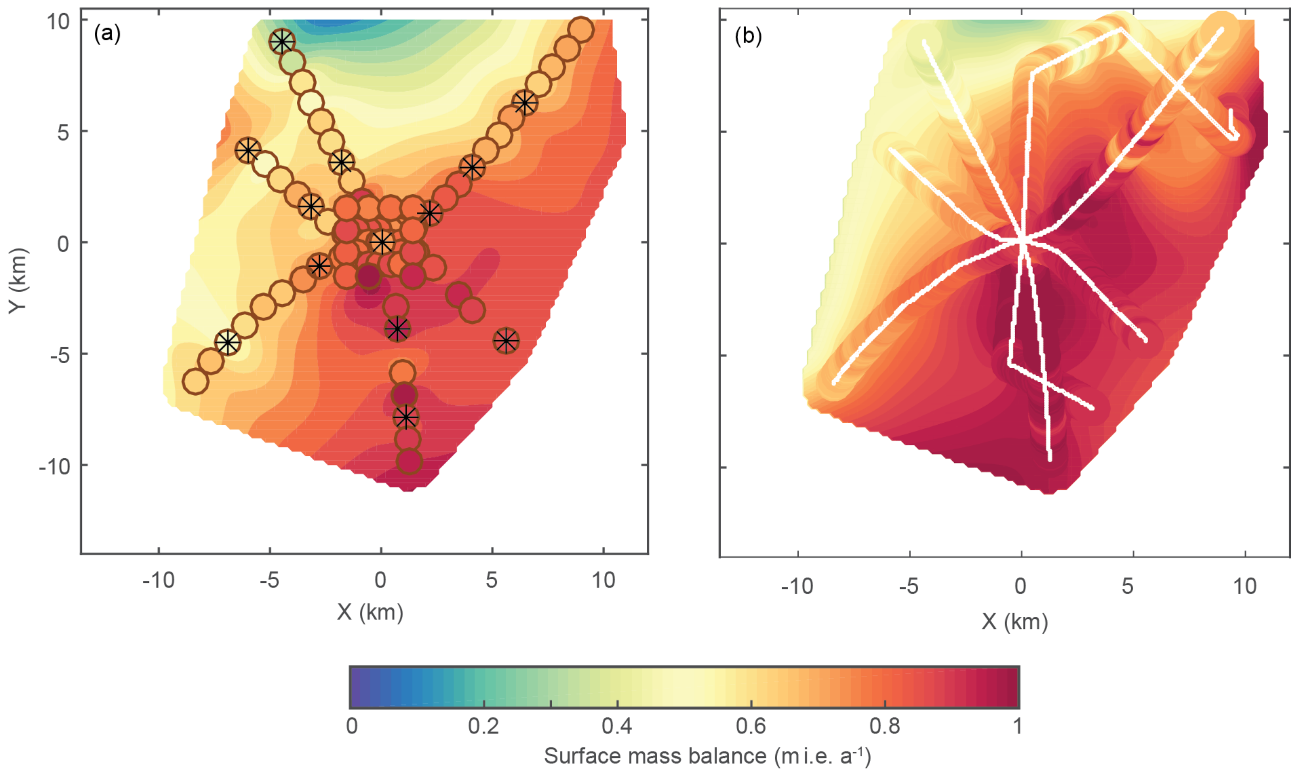

Figure 4. Surface mass balance (SMB). (a) SMB estimated with stake ~~methods over the~~ method during 2013-14. Circles show the locations of the installed stakes. Wheel spokes inside of the circles show the locations of 13 surface-density measurements. (b) SMB estimated ~~with~~ from radar over the past decade, ~~by~~ accounting only from the vertical variability of density. White curves show radar profiles. The 23 m long firn core was drilled near the crossover of all profiles at the summit.

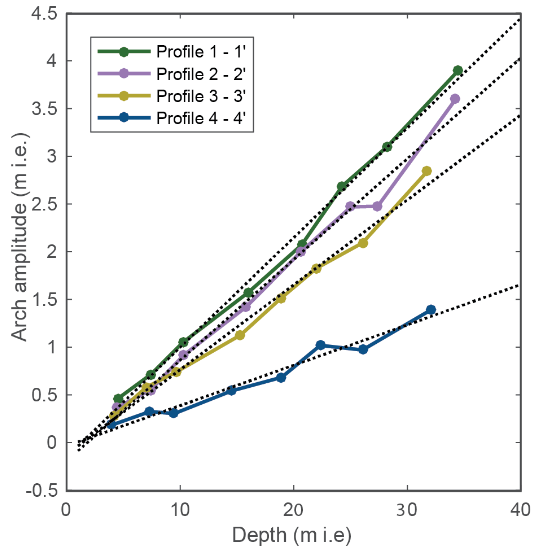

Figure 5. Depth variations of upward-arch amplitudes observed near the summit (Fig. 2b) along four radar profiles (Fig. 1b). ~~Dots~~ Filled circles show the arch amplitudes and ~~dashed~~ dotted lines show the linear fits~~of the arch amplitudes to depth~~.

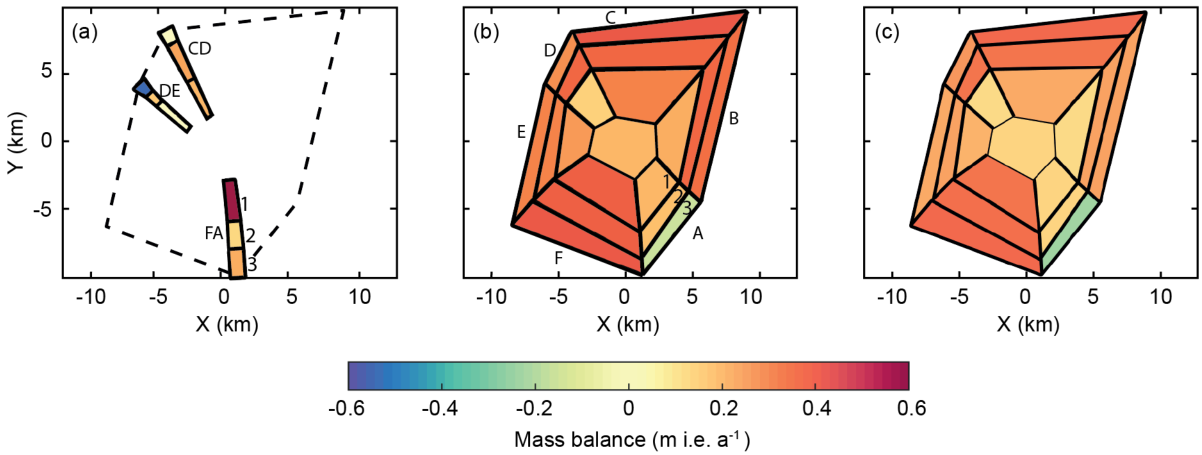

Figure 6. Recent mass balance ~~derived with three different setups~~ when the fraction γ of depth-averaged flow speed to the surface flow speed ~~is equal to~~ equals 0.8. Results are derived from three setups. (a) Flowband setup. The slopes (FA, CD and DE) are divided in to 3 columns (1–3, with 1 for most upstream in each slope). (b) Polygon setup. The ice rise is divided into 6 slopes (A–F) with 3 polygons (1–3, with 1 for most upstream in each slope) and a summit polygon. (~~b~~c) Grid setup. ~~(c) Flowband setup.~~ The dashed lines in (a) show the extent of the polygon and grid setups for comparison.

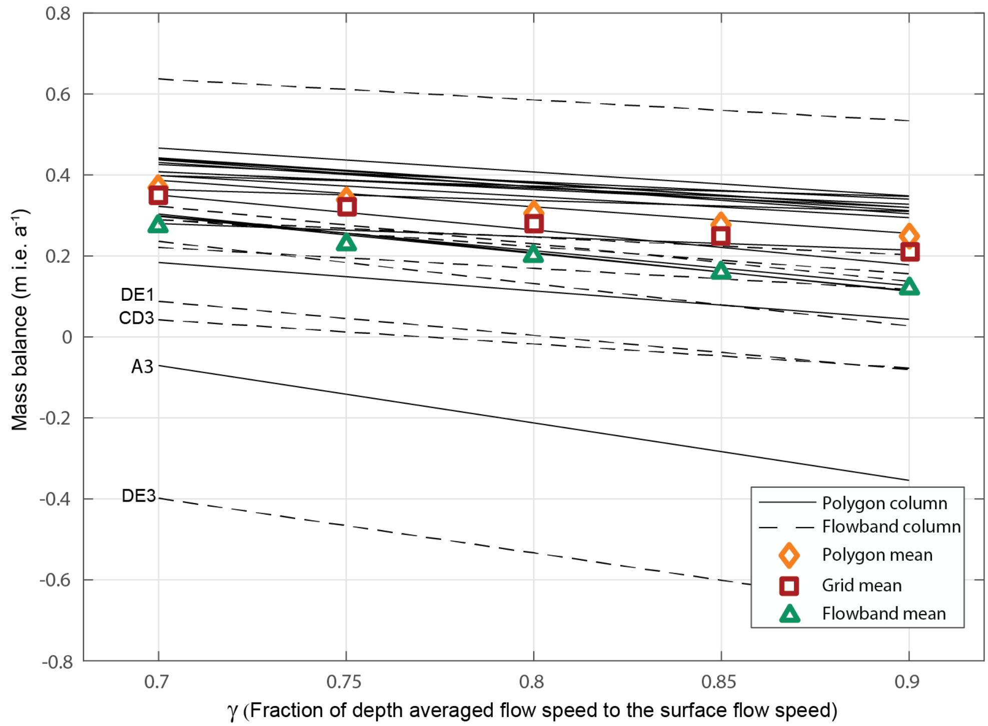

Figure 7. ~~Mass balance~~ Mass-balance estimates of individual polygonal ~~column~~ columns (~~Polygon~~ polygon setup, solid lines) and flowband columns (~~Flowband~~ flowband setup, dashed lines) in terms of γ, the fraction of the depth averaged flow speed to the surface flow speed. Those derived with the grid setup (not shown) are very similar as those with the polygon setup. The ensemble-mean mass balance estimates for each γ are shown with symbols for all the setups. Columns discussed in the text are labelled.