

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

This paper investigates the mechanism behind the substantial mass loss for glaciers on Svalbard over the last few decades.

The importance of meltwater refreezing and the hypsometry of Svalbard glaciers is evaluated and the results are generally presented well and give useful insight into the very negative glacier mass balance in this region. Modelled results are compared with in situ and satellite measurements. This topic is one of great importance but where there is widespread confusion, even amongst glaciologists working in mountain or ice sheet environments, and thus is important to scientists in this and related fields.

Considering this journal is general, a considerable amount of prior knowledge is taken for granted in this paper. Terms and methods are mentioned (e.g. statistical downscaling; in situ measurements) with no references or additional text. This is acceptable in a specialist journal, but Nature Communications is read by a more general audience.

Apart from this most of the comments and suggested changes are cosmetic and are intended make the paper easier to understand.

The concept of "tipping point" is very applicable here, and considering previous work by the lead author, I was surprised it was not used. Reference to IPCC SROCC chapter 6 (or other useful reference) could be used.

Only one surge is mentioned. The cumulative effects of other surges should at least be considered.

Comments by line number:

1-3: First sentence – hard to understand, obtuse, and the second part of sentence doesn't follow on from first.

3: "efficient" necessary in abstract?

6: "hypsometry peak"- as the journal is non-specialist, this should be defined or non-specialist terminology used.

1-12: much of abstract is written as though one already has knowledge of the paper.

17: Define "arctic amplification" – especially as the reference referred to is not a published scientific article and the URL provided is obsolete and an error message in Norwegian pops up.

18-19: "Mountains locally peak at 19 1,717 m a.s.l." – "The highest point on Svalbard is 1717 m a.s.l." [this should also be checked as two different heights appear to be reported for this peak]

23-24: Include newer references, e.g. Wouters et al., 2019; Zemp et al., 2019

35: Both PDD and EBM are used only twice, hence acronyms are unnecessary and the phrase can be written out both times.

36: What does "a decin SMB" mean? Better to write – more negative surface mass balance (or lower winter accumulation, higher summer ablation as appropriate).

37: A reference (or brief explanation) of statistical downscaling should be given here, for readers unfamiliar with the technique.

48: "these northern ice caps" – ambiguous. I assume this refers just to ice caps on Svalbard, but could be interpreted to mean all ice caps in the north (Arctic).

51 (and 199-206): more information and/or references would be useful (both for non-glaciologists and for specialists) to explain what understood by in situ measurements. [or include in supplementary material if not room in main text]

65-67: were all other surges insignificant? How sure is calving term for 1958 – 1984, as large surges in this period may be undetected? Need more information.

73-82: It would be helpful to compare this with mass balance measurements on one or two glaciers with a record of several decades (although pattern not straightforward)

92: unnecessary detail – delete "both" and "at 700 hPa and"

93: insert "average" in front of equilibrium

93: the term "migrated" suggests a steady change. Suggest rewording this.

96: change "evidenced" to "as shown"
100: delete "now"
109: change to: (as shown by marked hypsometry peak.....)
109-110: delete "located at" (misleading when the elevation given is an average and interval)
144: change "oscillates" to "fluctuates"
147-148: change "two times more than the" to "twice as large as"
149: change "beyond" to "above"
152: replace "quasi-irreversible" by "irreversible" or "probably irreversible" as appropriate
161: change "input of" to "input to"
170: Are there also 40 snow/firn layers? If so, "The" should be deleted as misleading.
187: Replace "detailed" with "described".
188: Change "1.6 Gt yr-1 on average" to "an average of 1.6 Gt yr-1".
191: Insert "respectively" after Svalbard.
199: Delete "Here".
203: Delete "a"
215-216: "constant elevation rate" is an unusual expression and ambiguous. Please reword.
222: Insert reference for value of density used.
234: Is the value of 700m correct? It seems inconsistent with the rest of the text.
235: change "allow to discard" to "allow the elimination of"
236: change "as e.g." to "such as".

Figures

Figure 1: The inset map in 1b is too small to be useful. Delete the map and spell out the acronyms in the box instead. Write out SMB in the figure caption (SMB is defined in the text AFTER the first reference to figure 1). Change "The x-axis shows the glaciated area at each elevation level" to "The x-axis shows the glaciated area in each 100-m elevation band".

Supplementary Information

Line 27: Kohler is misspelled.

Fig 2c: The ICESat points are hard to see. The figure would be clearer if a darker colour was used for ICESat. Swapping the colours for ICESat/Cryosat-2 and SMB would help.

Fig 3a: There is a lot of useful information in this figure, but it's difficult to see. Perhaps simply making the graph taller would help.

Fig 3c: The key to symbols should be lines not dots.

Fig 4e: the black line delineating the ELA for 1985-2018 is hardly visible, except on Austfonna. A white line would be clearer.

- Miriam Jackson

Review of Noel et al., Svalbard glaciers

The paper is well-written, a valuable contribution to the growing Svalbard literature and it addresses a timely topic. The paper appears sound, although see general comment below which hampers evaluating this fully. My main concern (which can probably be easily addressed?) is that overall it is not quite clear what is new: obviously there have been many reconstructions and mass balance studies in the recent past which the authors cite, and the higher sensitivity due to the low elevation has been pointed out before. Perhaps it can be emphasized more what this study adds to this bulk of recent literature and the new results put in better context of the existing reconstructions which are barely mentioned.

Note, I make a number of comments where an issue occurs the first time but the comment may also hold for other places where I don't repeat the comment.

General

- 1) There are a number of terminology issues not consistent with Cogley et al., 2011 (Mass balance glossary), some of them make it difficult to evaluate if some of the methods are sound: SMB strictly speaking only refers to the surface balance (which ablation stakes measure) and not refreezing. The latter is included in the 'climatic mass balance'. It appears that what is modeled is the climatic balance and not the surface mass balance. This distinction is in particular important when it comes to comparison with in-situ stake measurements since these can only make surface mass balance and not the climatic balance. So, it is not clear if the evaluation was done comparing apples with pears (Supp Fig. 2), and thus if the evaluation is sound.
I recommend that the authors stick to Cogley et al., 2011.
- 2) It is also unclear how precipitation was treated. Rain fall does not contribute to mass balance (unless it refreezes). Do the authors mean snowfall when they say precipitation? Does the balance exclude rain that does not refreeze?
- 3) The term refreezing capacity is unclear. How is it defined? It appears that it is used in the sense of just 'refreezing' and not some sort of 'capacity' or ratio to pore space or so?
- 4) There is too many acronyms which are not necessary. There is generally enough space in the figures to spell them out and make the paper more readable to a broader audience.
- 5) Often in the text, the model results come across as 'facts'. It needs to be clearer that most results are modeled results.
- 6) It is not clear why the decline in the firn area and its associated capacity to store refrozen water is irreversible. If the climatic balance turned positive for sufficiently long time, the firn area would expand and thicken and with it allow more refreezing. So, the point of irreversibility appears speculative.

Detailed comments

- 7) Term 'Glaciated' is not used according to Cogley et al, 2011. → Glacierized or just glacier area

- 8) Line 1: this sentence is not appropriate for Nature readership. Isn't most important to convey that there is a lot of area below 450 m (or 500 m to round it). In theory a peak in the hypsometry can be extremely low but 90% of the area above. What matters is not just the peak but the distribution, so this may better be framed differently here and below.
- 9) Line 3: replace 'exist' by 'survive' since they do exist now
- 10) Overall the abstract is not very clear and seems not adequate for a broader readership; it's also not clear if this is observations or modeling results.
- 11) Line 8: 'dry climate'
- 12) All elevations should be m a.s.l., not just m
- 13) line 16, ref 3 is cited although an update by Farinotti et al 2019 exists
- 14) Line 21-22: again, the peak is not necessarily important, but how much area is below a certain elevation. E.g. at what elevation is X % of the area in these different regions.
- 15) Line 28
Terminology: SMB strictly speaking only refers to the surface balance (which ablation stakes measure) and not refreezing. The latter is included in the 'climatic mass balance'. Here it is the climatic balance
- 16) Line 49: vague: what kind of 'future warmer climate'.
- 17) Line 52/53: remove "yellow stars" and "in the ablation (blue)". This holds for other places in the manuscript as well. Please remove any reference to colors or symbols in the main text – this should only be in the captions. Just refer to the appropriate figure.
- 18) Line 53: what time periods do these 1611 measurements cover: are they annual balances, winter, summer, other periods?
- 19) Line 59 after "Fig 1a" to line 61: remove. The caption /figure shows these sectors
- 20) Line 75: I assume the authors mean 'net mass loss' since mass loss happens every year even in years with positive mass balance.
- 21) Line 79: 'confirms the large fluctuations': it is unclear what it confirms? Has this result been found by others and published and here your model comes up with the same result?
- 22) Line 88, not sure if 'mitigating' is the right word here
- 23) Line 98: why +62% this is unclear

- 24) Line 102: decline should be change if negative numbers follow
- 25) Line 161: remove 'In brief'
- 26) Methods: how is firn extent models?
- 27) 40 snow layers: how deep are subsurface processes modeled and how deep is the firn in Svalbard?
- 28) Modelled ELA: the method is unorthodox and can lead to very different results than when done as typically done, i.e. estimated from the mass balance gradient (where it's zero). Esp when ELAs are not rather straight lines, deviations can be large.
- 29) Line 157: bold statement without any evidence? Where does this come from
- 30) Overall a number of **figure captions** should be improved (I give some examples below). Often the first line reads like a campaign slogan. Best just to state what is shown rather than a 'conclusion like statement', e.g. 'Strong sensitivity' Also when there is a legend the colors of lines etc don't need to be repeated in the caption. Many caption can be shortened and thus become better readable.
- 31) **Figure 1:**
- color scale: would be better to reverse with positive numbers at top
 - yellow stars are almost impossible to see and the shape not at all. Perhaps just dots and a more distinguishable color
 - remove acronyms for plot b. They are not necessary and only make this figure hard to grasp – there is lots of space to spell out each region. GrIS: Greenland ice sheet, GIC: Greenland periphery or Greenland glaciers; NCAA: S Canadian Archipelago ... (the domain is clear from the map, 'Arctic' not needed). Same for Svalbard map, the full region names could be spelled out.
 - the inset map may be easier to read if it had a box
- 32) Figure 1 caption:
- add 'modeled' to caption in first line
 - 'elevation level': is this elevation band? Binning interval needs to be stated.
- 33) **Figure 2:**
- colors don't need to be repeated in the caption, there is a legend
 - legend is a bit confusing since all is mass balance, i.e. some form of mass change; and it's not immediately clear that there are 3 components shown based on this study and 3 sets of observational data sets. Perhaps the legend can be split into two columns?
 - green for both ICESat and CryoSat is not well visible
 - A color scheme suitable for color-blind people should be chosen
 - the Discharge curve is misleading since it looks like it is a mass gain (negative sea level rise). The problem is the lack of consistency in sign convention (gain +, losses -). This convention is followed for all curves but D. This needs to be fixed somehow best with using consistent sign convention, i.e. the D curve becomes a negative mass change.
 - Caption better: Modeled and observed mass changes and contr. ... Not clear why 'Onset', it shows more than that.

34) Figure 3:

- a) spell out acronyms. There is enough space.
- b) caption: remove 'irreversible'
- c) caption: remove 'cumulative', it's not cumulative but the rate
- d) plot c: replace 'Integrated area' by Area
- e) plot c: the legend is confusing. Better (e.g. in 3 rows): Modeled ablation area, Modeled bare ice area, Observed bare ice area (MODIS)

Figure 4

- a) Remove JJA from axis label and put in caption: .. (a) 2 m summer (JJA) air temperature anomaly and ELA
- (b) remove 'change'
- also all other variables, just give the variable and no direction of change

Supplementary material

Figure S1: scale or coordinates missing

Figure S1 Legend:

- a) add 'modeled': Time series of modeled ...
- b) It's unclear why the right y-axis is only for the post-1985 mass loss. Doesn't the translation hold for the entire period?
- g) Can be added in the caption

Figure S2:

- a) Plot a: y-axis label: remove Downscaled and at 0.5 km, that can be in the caption
- b) Caption: Evaluation of what?
- c) Plot c: legend is confusing. All is mass balance, the difference is that the blue is modeled: replace 'Mass balance' by 'Modeled'
- d) Plot b: there should some sort of multiplication symbol between the bias/rmse numbers and the 10^3
- e) Plot b: spell out legend acronyms; there is sufficient space

Figure S3:

- a) The acronyms are not needed and should be spelled out for easier readability

Figure S4:

- a) The caption: upward migration of the ELA seems misleading. I see the SMB and runoff change but no migration?
- b) The ELA for the 2 periods is not readable
- c) For clarity: 1985-2018 would be better in legend

Supple Table 1

- a) Comparison of what? Comparison of modeled and recent estimates.

- b) Explain PDD and EBM in caption, also WRF and MAR

Supple Table 2

- a) What's cap? How is it defined? The decimals seems not warranted, same for Ablation area
- b) What are the uncertainties for ELA?
- c) It might be better to call the ice masses just glaciers instead of ice caps, since I assume the table includes not only those ice masses that are from a morphological point an ice cap?

It would be useful if Figure 3a (main text) could also be expressed in specific units for comparison with mass change rates in other regions/studies. If the area was constant throughout the time period this could just be added as a second y-axis. If not perhaps another figure in the supplementary?

Response to reviewers

Dear reviewers, we would like to thank you for your constructive comments which greatly improved our manuscript. To facilitate readability of this document, our responses to reviewers are displayed in blue and modifications in the manuscript are highlighted in red. These suggested changes, together with additional minor corrections, are also displayed in red in the attached revised manuscript.

Reviewer #1: Miriam Jackson

This paper investigates the mechanism behind the substantial mass loss for glaciers on Svalbard over the last few decades. The importance of meltwater refreezing and the hypsometry of Svalbard glaciers is evaluated and the results are generally presented well and give useful insight into the very negative glacier mass balance in this region. Modelled results are compared with in situ and satellite measurements. This topic is one of great importance but where there is widespread confusion, even amongst glaciologists working in mountain or ice sheet environments, and thus is important to scientists in this and related fields. Thank you.

General comments:

1. Considering this journal is general, a considerable amount of prior knowledge is taken for granted in this paper. Terms and methods are mentioned (e.g. statistical downscaling; in situ measurements) with no references or additional text. This is acceptable in a specialist journal, but Nature Communications is read by a more general audience. We agree and revised the manuscript accordingly. See e.g. our responses to comments in L1-12, L37 and L51.
2. Apart from this most of the comments and suggested changes are cosmetic and are intended make the paper easier to understand. Thank you for thoroughly reading our manuscript, please find our corrections hereunder.
3. The concept of "tipping point" is very applicable here, and considering previous work by the lead author, I was surprised it was not used. Following the general comment #6 of reviewer #2, we removed the "tipping" or "irreversibility" aspect as this implies that recent mass loss will persist irrespective of future conditions even on the longer-term (centuries to millennia). Please, see our response to general comment #6 of reviewer #2.
4. Reference to IPCC SROCC chapter 6 (or other useful reference) could be used. The SROCC report is now referred to in the manuscript.
5. Only one surge is mentioned. The cumulative effects of other surges should at least be considered. Surging glaciers are common and widespread in Svalbard. Farnsworth et al. (2016) identified 708 Svalbard glaciers that have likely surged in the past. While the surging feature of Svalbard glaciers is well known (e.g. Hagen et al., 2003; Blaszczyk et al., 2009), surge events are poorly documented and understood. Only recent surges are described for a few glaciers in NW, SS and NE Svalbard (e.g. Sund et al., 2014; Sevestre et al., 2018; Nuth et al., 2019), and actual calving rates ($4.2 \pm 1.6 \text{ Gt yr}^{-1}$) were only estimated for the recent 2012-2013 surge of a major glacier in Austfonna (McMillan et al., 2014; Dunse et al., 2015). Finally, Blaszczyk et al. (2009) is the only study that provides Svalbard-wide calving flux estimates for 2000-2006 ($D = 6.8 \pm 1.7 \text{ Gt yr}^{-1}$), which we used in this paper. In addition, we included the post-2012 mass loss acceleration in Austfonna (Dunse et al., 2015). Unfortunately, based on the available literature, the cumulative effect of past surges cannot be accounted for. We inserted the following information in L32-37 as: "Surge-type glaciers strongly impact D and are widespread in Svalbard¹⁴, with more than 700 glaciers that likely surged in the past¹⁵. Although surge events can strongly influence mass loss locally¹⁶, these events are poorly understood and are only documented for a few glaciers¹⁷⁻¹⁹. Here we use a Svalbard-wide solid ice discharge estimate for the period 2000-2006¹³, complemented by an increase in D after the surge of a major Austfonna glacier in 2012-2013²⁰". See also our response to comment in L65-67.

Comments by line number:

1-3: First sentence – hard to understand, obtuse, and the second part of sentence doesn't follow on from first. We reformulated the abstract as: "Compared to other Arctic ice masses, Svalbard glaciers are low-elevated with flat interior accumulation areas, resulting in a marked peak in their current hypsometry (area-elevation distribution) at ~450 m above sea level. Since summer melt consistently

exceeds winter snowfall, these low-lying glaciers can only survive by refreezing a considerable fraction of surface melt and rain in the porous firn layer covering their accumulation zones. We use a high-resolution climate model to show that modest atmospheric warming in the mid-1980s forced the firn zone to retreat upward by ~100 m to coincide with the hypsometry peak. This led to a rapid areal reduction of firn cover available for refreezing, and strongly increased runoff from dark, bare ice areas, amplifying mass loss from all elevations. As the firn line fluctuates around the hypsometry peak in the current climate, Svalbard glaciers will continue to lose mass and show high sensitivity to temperature perturbations.”

3: “efficient” necessary in abstract? This is now removed. See also the previous comment in L1-3.

6: “hypsometry peak”- as the journal is non-specialist, this should be defined or nonspecialist terminology used. The term hypsometry is now defined as: “(area-elevation distribution)”.

1-12: much of abstract is written as though one already has knowledge of the paper.
We reformulated the abstract, see our response to comment in L1-3.

17: Define “arctic amplification” – especially as the reference referred to is not a published scientific article and the URL provided is obsolete and an error message in Norwegian pops up. We define Arctic Amplification in L15-17 following Chapter 3 of the SROCC report: “As a result of Arctic Amplification³, in which Arctic warming over the last two decades was twice the global average⁴, and being situated at the edge of retreating Arctic sea ice, Svalbard ice caps experience among the fastest warming on Earth.”. The corrupted URL has been fixed.

18-19: “Mountains locally peak at 19 1,717 m a.s.l.” – “The highest point on Svalbard is 1717 m a.s.l.” [this should also be checked as two different heights appear to be reported for this peak]
The value of 1,717 m a.s.l. is from Van Pelt et al. (2019). The exact value is not essential and we decided to round it to ~1700 m a.s.l. in L18-21 as: “The highest elevation on Svalbard is approximately 1,700 m a.s.l. (above sea level), but the glacier hypsometry (area-elevation distribution) peaks at ~450 m a.s.l., compared to 800-1,400 m a.s.l. for ice caps in Greenland, Arctic Canada and Iceland (Fig. 1b).”.

23-24: Include newer references, e.g. Wouters et al., 2019; Zemp et al., 2019. Done. We also included the recent work of Schuler et al. (2020) in L46-47: “Similar conclusions were drawn by upscaling in situ SMB measurements to all Svalbard land ice¹², but little remains known about the temporal and spatial variability of the surface mass loss.” ; and added their mass balance estimates in Table S1 in the Supplementary Material.

35: Both PDD and EBM are used only twice, hence acronyms are unnecessary and the phrase can be written out both times. Indeed, thank you. Acronyms have been removed accordingly.

36: What does “a decline SMB” mean? Better to write – more negative surface mass balance (or lower winter accumulation, higher summer ablation as appropriate). We reformulated as: “increase in summer ablation (Table S1)”.

37: A reference (or brief explanation) of statistical downscaling should be given here, for readers unfamiliar with the technique. We now briefly explain the downscaling technique in L53-56 as: “The method primarily corrects daily melt and runoff for elevation biases on the relatively coarse RACMO2.3 model grid using elevation gradients, and for underestimated ice albedo using remote sensing measurements²⁸ (see Methods).”.

48: “these northern ice caps” – ambiguous. I assume this refers just to ice caps on Svalbard, but could be interpreted to mean all ice caps in the north (Arctic). We reformulated as: “Svalbard ice caps”.

51 (and 199-206): more information and/or references would be useful (both for non-glaciologists and for specialists) to explain what understood by in situ measurements. [or include in supplementary material if not room in main text]. We reformulated L67-69 as: “The SMB product is evaluated using

1,611 local (in situ) annual balance measurements from 101 sites (Fig. 1a) collected in the ablation and accumulation zones of Svalbard glaciers over the period 1967-2015 (see Methods; Fig. S2a).” and described the in situ sites and measurements in the Method section in L232-238 as: “We use 1,611 local (in situ) annual balance measurements covering the period 1967-2015 and collected at 101 sites (Fig. 1a) on Austre Brøggerbreen, Midtre Lovénbreen, Kongsvegen and Holtedahlfonna glaciers in NW Svalbard^{42,43}; Hansbreen glacier in SS sector⁴⁴; Austfonna ice cap²² and Nordenskiöldbreen glacier in NE Svalbard⁴⁵. Stake annual balance is estimated as the elevation difference between two consecutive end-of-summer surface heights (September). For a meaningful comparison, modelled SMB was integrated between September 15 of two consecutive years.”. Appropriate references to the data sets have also been inserted accordingly.

65-67: were all other surges insignificant? How sure is calving term for 1958 – 1984, as large surges in this period may be undetected? Need more information. Surges are common in Svalbard but poorly documented with no calving estimates. Blaszczyk et al. (2009) provide the only Svalbard-wide estimate of solid ice discharge for the period 2000-2006 ($6.8 \pm 1.7 \text{ Gt yr}^{-1}$). To the authors’ knowledge, Dunse et al. (2015) is the only study that quantifies mass loss from the major surge event in Austfonna in 2012-2013 ($4.2 \pm 1.6 \text{ Gt yr}^{-1}$). Therefore, we assumed that the 2000-2006 solid ice discharge flux of Blaszczyk et al. (2009) was valid for the whole study period, and included the recent contribution of Austfonna after 2012 (Dunse et al., 2015) in very good agreement with remote sensing. We clarified this in L83-89 as: “We assume that solid ice discharge estimate for 2000-2006 ($D = 6.8 \pm 1.8 \text{ Gt yr}^{-1}$)¹³ is valid for the whole study period (1958-2018). In line with Dunse et al. (2015)²⁰, we increase solid ice discharge by $4.2 \pm 1.6 \text{ Gt yr}^{-1}$ from 2012 onwards, following the surge of a major Austfonna outlet glacier. Combining this with the downscaled SMB product, we reconstruct the mass change of Svalbard glaciers over the last six decades (Fig. 2). The modelled mass change is obtained by integrating both SMB and D in time starting from zero in 1958. Our reconstruction agrees very well with remote sensing records from GRACE [...]”.

73-82: It would be helpful to compare this with mass balance measurements on one or two glaciers with a record of several decades (although pattern not straightforward). Compared to previous studies we are aware of, the model evaluation presented here is already very comprehensive and agrees well with in situ/remotely sensed observations. Therefore, we feel that that additional comparisons are not necessary to further support the quality of our product.

92: unnecessary detail – delete “both” and “at 700 hPa and”. Done. 93: insert “average” in front of equilibrium. Done. 93: the term “migrated” suggests a steady change. Suggest rewording this. We replaced “migrated” by “moved”. 96: change “evidenced” to “as shown”. Done. 100: delete “now”. Done. 109: change to: (as shown by marked hypsometry peak.....). Done. 109-110: delete “located at” (misleading when the elevation given is an average and interval). Done. 144: change “oscillates” to “fluctuates”. Done. 147-148: change “two times more than the” to “twice as large as”. Done. 149: change “beyond” to “above”. Done. 152: replace “quasi-irreversible” by “irreversible” or “probably irreversible” as appropriate. We reformulated in L173-174 as: “We conclude that the post-1985 decline in refreezing capacity will persist under continued warming: [...]”. See also our response to general comment #3. 161: change “input of” to “input to”. Done. 170: Are there also 40 snow/firn layers? If so, “The” should be deleted as misleading. Yes, RACMO2 has 40 snow layers. We reformulated as: “The model also includes 40 active snow layers [...]”. 187: Replace “detailed” with “described”. Done. 188: Change “1.6 Gt yr-1 on average” to “an average of 1.6 Gt yr-1”. Done. 191: Insert “respectively” after Svalbard. Done. 199: Delete “Here”. Done. 203: Delete “a”. Done. 215-216: “constant elevation rate” is an unusual expression and ambiguous. Please reword. We reformulated as: “[...] estimated by adding the elevation rate of the fitted model to the residuals.” 222: Insert reference for value of density used. We refer to Wouters et al. (2015) in which the technique is described in detail. 235: change “allow to discard” to “allow the elimination of”. Done. 236: change “as e.g.” to “such as”. Done.

234: Is the value of 700m correct? It seems inconsistent with the rest of the text. As shown in Fig. 3b, long-term ELA of Svalbard (and individual sectors; see Table S3) remains well below 700 m a.s.l. Only in extremely warm summers (2003 and 2013; Fig. 3b) does the Svalbard-wide ELA reach elevations of $600 \pm 80 \text{ m a.s.l.}$ In addition, Fig. 3c highlights that the ELA remains above the bare ice zone as the

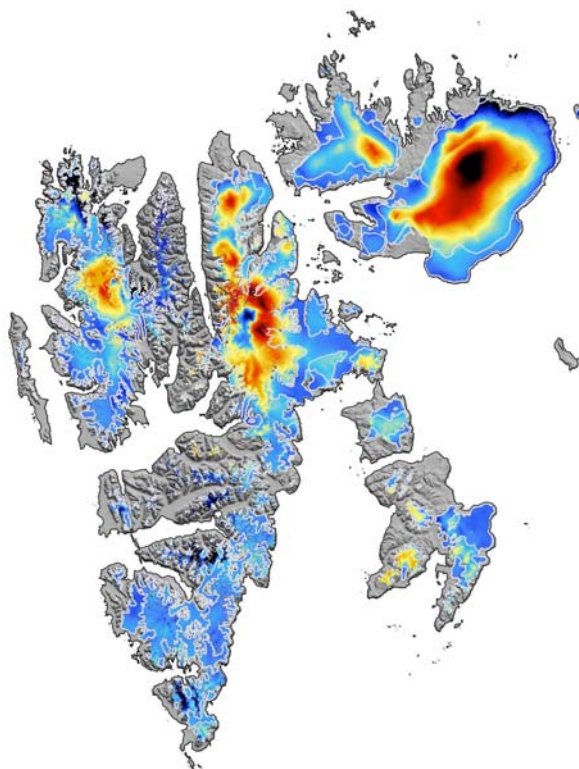
upper ablation zone also includes a narrow band exposing superimposed ice. Therefore, an upper elevation threshold of 700 m was judged appropriate to eliminate spurious snow free pixels in our MODIS albedo product that result from e.g. superimposed ice, meltwater lakes or bare rocks. This is now clarified in L271-274 as: “and iii) the pixel is located below 700 m a.s.l., which is well above the long-term ELA of Svalbard (440 ± 80 m a.s.l. for 1985-2018) and individual sectors (up to 550 ± 65 m a.s.l. in NW; Table S3). Even in extremely warm years such as 2003 and 2013, the Svalbard-wide ELA (600 ± 80 m a.s.l.; Fig. 3b) remains below the selected elevation threshold.”.

Comments on Figures:

Figure 1: The inset map in 1b is too small to be useful. Delete the map and spell out the acronyms in the box instead. **Done.** Write out SMB in the figure caption (SMB is defined in the text AFTER the first reference to figure 1). **Done.** Change “The x-axis shows the glaciated area at each elevation level” to “The x-axis shows the glaciated area in each 100-m elevation band”. **Done.**

Supplementary Information

Line 27: Kohler is misspelled. **Thank you for pointing that out! This is corrected.** Fig 2c: The ICESat points are hard to see. The figure would be clearer if a darker colour was used for ICESat. Swapping the colours for ICESat/Cryosat-2 and SMB would help. **We prefer not swapping colours between ICESat/CryoSat-2 and SMB to be consistent with Fig. S2c.** For clarity, ICESat data are now shown in light blue and we increased the marker size. For consistency, similar changes were applied to Fig. S2c. Fig 3a: There is a lot of useful information in this figure, but it’s difficult to see. Perhaps simply making the graph taller would help. **Enlarging Fig. 3a is difficult given the other three time series below and the second y-axis requested by reviewer #2. We hope that it is now better readable.** Fig 3c: The key to symbols should be lines not dots. **Done.** Fig 4e: the black line delineating the ELA for 1985-2018 is hardly visible, except on Austfonna. A white line would be clearer. **As suggested, we used a white line to outline the ELA but were not satisfied with the end result (see attached figure hereunder), and decided to leave Fig. 4e as is. If judged necessary by the editor, we can revise Fig. 4e.**



Reviewer #2: Anonymous

The paper is well-written, a valuable contribution to the growing Svalbard literature and it addresses a timely topic. The paper appears sound, although see general comment below which hampers evaluating this fully. [Thank you.](#)

My main concern (which can probably be easily addressed?) is that overall it is not quite clear what is new: obviously there have been many reconstructions and mass balance studies in the recent past which the authors cite, and the higher sensitivity due to the low elevation has been pointed out before. [We present a new SMB data set for Svalbard that, for the first time, reconstructs realistic mass balance in space and time at high spatial \(500 m\) and temporal \(daily\) resolution over the last six decades. We demonstrate that the results are in close agreement with recent remote sensing estimates and long-term mass change from previous studies \(Table S1\). Our results highlight that Svalbard glaciers have experienced large spatial and temporal mass loss variability since the mid-1980s and enable a process-based interpretation, namely rapid fluctuations of the firn line around the peak in glacier hypsometry. To the authors' knowledge, no previous studies have quantified these processes in similar detail. This is stressed in L58-65 as: "Combined with discharge estimates^{13,20}, our high-resolution SMB product enables us to estimate the spatially and temporally varying mass balance of Svalbard glaciers over the last six decades, including the high mass loss variability starting in the mid-1980s. We show that a modest atmospheric warming of 0.5°C in the mid-1980s was sufficient to raise the firn line to the hypsometry peak at ~450 m a.s.l., exposing large parts of the accumulation area to increased melt. The subsequent loss of refreezing capacity, i.e. the fraction of rain and meltwater retained or refrozen in firn \(see Methods\), implies that Svalbard ice caps can no longer be sustained when the current climate persists or further warming occurs."](#)

Perhaps it can be emphasized more what this study adds to this bulk of recent literature and the new results put in better context of the existing reconstructions which are barely mentioned. [In the introduction, we provide a comprehensive collection of recent studies that estimated the \(surface\) mass balance of Svalbard using various techniques \(e.g. regional climate models, positive degree day and energy balance models, GRACE, geodetic and in situ measurements; see L37-46 in the revised manuscript\). Addressing the comments in L23-24 and general comment #5 of Reviewer #1, we now also include the recent work of Zemp et al. \(2019\) and Schuler et al. \(2020\), and added a dedicated paragraph on the contribution of solid ice discharge from surge-type glaciers to the mass balance of Svalbard \(see L27-36\), including the work of Sund et al. \(2014\), Farnsworth et al. \(2016\), Sevestre et al. \(2018\) and Nuth et al. \(2019\). In addition, we provide a comprehensive assessment of mass balance estimates derived from 14 studies, and compare them with our reconstructed product in Table S1. We deem that our approach keeps the manuscript concise and focused on our main message. A detailed assessment of techniques previously used to estimate \(surface\) mass balance of Svalbard is available in e.g. the recent Review Article of Schuler et al. \(2020\).](#)

Note, I make a number of comments where an issue occurs the first time but the comment may also hold for other places where I don't repeat the comment. [These remarks have been accounted for across the revised manuscript.](#)

General comments:

1) There are a number of terminology issues not consistent with Cogley et al., 2011 (Mass balance glossary), some of them make it difficult to evaluate if some of the methods are sound: SMB strictly speaking only refers to the surface balance (which ablation stakes measure) and not refreezing. The latter is included in the 'climatic mass balance'. It appears that what is modeled is the climatic balance and not the surface mass balance.

[Indeed, our use of 'surface mass balance' \(SMB\) includes 'internal accumulation' \(refreezing and retention\), and conforms to a quantity that is formally referred to as 'climatic mass balance' in Cogley et al. \(2011\). However, the use of SMB conforms to previous studies for Canadian ice caps, Greenland ice caps and the Greenland ice sheet \(Noël et al., 2017, 2018, 2019\) and Svalbard \(Van Pelt et al., 2019; Lang et al., 2015\). Our way of using SMB is also commonly found in widely cited ice sheet mass balance studies where the mass balance definition \$MB = SMB - D\$ \(solid ice discharge\) is used, e.g. Shepherd et al. \(2020; Nature\), Mouginot et al. \(2019; PNAS\). Given that our slightly different way of using 'surface mass balance' is widely used and accepted, we feel its current use is acceptable as long](#)

as it is clearly stated and defined in the manuscript, i.e. in the revised Methods section in L187-193 we now state: “In this study we refer to ‘surface mass balance’ (SMB) as both the local (kg m^{-2}) and spatially integrated (Gt yr^{-1}) sum of:

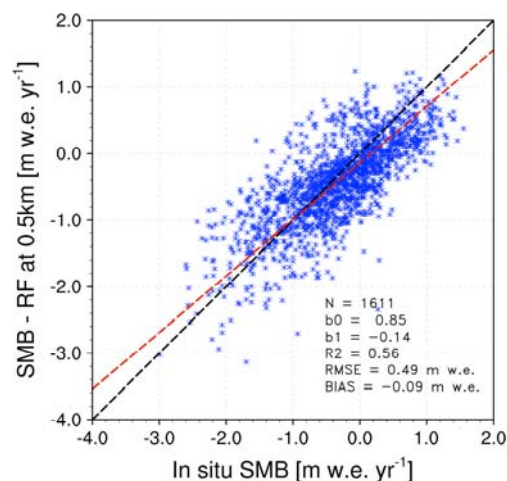
$$\text{SMB} = \text{PR} - \text{RU} - \text{SU} - \text{ER} \quad (1)$$

where PR represents total precipitation including snowfall (SF) and rainfall (RA), RU meltwater runoff, SU total sublimation and ER the erosion from drifting snow. Liquid water from rain and melt (ME) that is not retained/refrozen in firn (RF) contributes to runoff:

$$\text{RU} = \text{ME} + \text{RA} - \text{RF} \quad (2)$$

Note that in Cogley and others (2011)³⁷, the local quantity that includes ‘internal accumulation’ from refreezing/retention is referred to as ‘climatic mass balance’.

This distinction is in particular important when it comes to comparison with in-situ stake measurements since these can only make surface mass balance and not the climatic balance. So, it is not clear if the evaluation was done comparing apples with pears (Supp Fig. 2), and thus if the evaluation is sound. I recommend that the authors stick to Cogley et al., 2011. We agree that stake measurements from the percolation area (lower accumulation zone) and the interior accumulation zone do not include internal accumulation. To address this, we repeated the evaluation shown in Fig. S2a and compared in situ measurements to modelled “SMB minus RF”, where RF accounts for refreezing and retention, for sites located in the accumulation zone i.e. above the long-term Svalbard-wide ELA of 440 m a.s.l. (see Table S3). Not accounting for internal accumulation (i.e. refreezing) in the accumulation zone, we obtain very similar results to those shown in Fig. S2a, with a slightly larger RMSE (+50 mm w.e.) and smaller R^2 (-0.07). It is also important to note that in situ measurements suffer from relatively large uncertainties. Therefore, we deem that the evaluation shown in Fig. S2 remains valid and clarified this in L71-75: “Unlike the downscaled SMB product, stake measurements in the accumulation zone do not include internal accumulation from the refreezing of melt and rain (see Methods). Ignoring internal accumulation when comparing the model to stake measurements located in the accumulation zone leads to a small RMSE increase of $\sim 50 \text{ mm w.e. yr}^{-1}$ ”.



2) It is also unclear how precipitation was treated. Rainfall does not contribute to mass balance (unless it refreezes). Do the authors mean snowfall when they say precipitation? This is indeed confusing, by precipitation we mean “total precipitation” (PR) including both snow and rainfall. The revised manuscript now refers to “total precipitation” where appropriate. Does the balance exclude rain that does not refreeze? No rain that does not refreeze is considered part of surface runoff as in Eq. (2) above.

3) The term refreezing capacity is unclear. How is it defined? It appears that it is used in the sense of just ‘refreezing’ and not some sort of ‘capacity’ or ratio to pore space or so? Firn refreezing capacity is estimated as the fraction of rain and meltwater that is retained or refrozen in snow. This is now clarified in L63-65 as: “The subsequent loss of refreezing capacity, i.e. the fraction of rain and meltwater retained or refrozen in firn (see Methods), implies that Svalbard ice caps can no longer be sustained when the current climate persists or further warming occurs.”. The Methods section also

includes the following in L193-195: “Firn refreezing capacity (RFcap), i.e. the fraction of rain and meltwater effectively retained or refrozen in firn, is estimated as, $RFcap = RF / (ME + RA)$ (3)”.

4) There is too many acronyms which are not necessary. There is generally enough space in the figures to spell them out and make the paper more readable to a broader audience. The manuscript has been revised accordingly.

5) Often in the text, the model results come across as ‘facts’. It needs to be clearer that most results are modeled results. We made an effort to clarify that results are based on model outputs in the revised manuscript.

6) It is not clear why the decline in the firn area and its associated capacity to store refrozen water is irreversible. If the climatic balance turned positive for sufficiently long time, the firn area would expand and thicken and with it allow more refreezing. So, the point of irreversibility appears speculative. Our use of the term ‘irreversible’ indeed assumed persistence of current conditions or further warming, and not a future transition to colder conditions. So we agree that the loss of refreezing capacity might not be “irreversible” on centennial to millennial time scales. We therefore decided to tone down the “irreversibility” claim and reformulated L63-65 as: “The subsequent loss of refreezing capacity, i.e. the fraction of rain and meltwater retained or refrozen in firn (see Methods), implies that Svalbard ice caps can no longer be sustained when the current climate persists or further warming occurs.”, in L173-175 as: “We conclude that the post-1985 decline in firn refreezing capacity will persist under continued warming: a temporary [...] recovery of the refreezing capacity (Fig. 3d).”.

Detailed comments:

7) Term ‘Glaciated’ is not used according to Cogley et al, 2011. → Glacierized or just glacier area. We replaced “glaciated area” by “glacier area” where appropriate.

8) Line 1: this sentence is not appropriate for Nature readership. Isn’t most important to convey that there is a lot of area below 450 m (or 500 m to round it). In theory a peak in the hypsometry can be extremely low but 90% of the area above. What matters is not just the peak but the distribution, so this may better be framed differently here and below. We reformulated the abstract as: “Compared to other Arctic ice masses, Svalbard glaciers are low-elevated with flat interior accumulation areas, resulting in a marked peak in their current hypsometry (area-elevation distribution) at ~450 m above sea level. Since summer melt consistently exceeds winter snowfall, these low-lying glaciers can only survive by refreezing a considerable fraction of surface melt and rain in the porous firn layer covering their accumulation zones. We use a high-resolution climate model to show that modest atmospheric warming in the mid-1980s forced the firn zone to retreat upward by ~100 m to coincide with the hypsometry peak. This led to a rapid areal reduction of firn cover available for refreezing, and strongly increased runoff from dark, bare ice areas, amplifying mass loss from all elevations. As the firn line fluctuates around the hypsometry peak in the current climate, Svalbard glaciers will continue to lose mass and show high sensitivity to temperature perturbations.” Based on the data of Fig. 1b, we estimated that about 60% of the glacier area was below 450 m a.s.l. See also our response to comment #14.

9) Line 3: replace ‘exist’ by ‘survive’ since they do exist now. Done.

10) Overall the abstract is not very clear and seems not adequate for a broader readership; it’s also not clear if this is observations or modeling results. See our response to comment #8 above.

11) Line 8: ‘dry climate’. This is removed in the revised manuscript.

12) All elevations should be m a.s.l., not just m. Done.

13) line 16, ref 3 is cited although an update by Farinotti et al 2019 exists. Thank you for pointing that out! We updated the reference and associated values in L13-15: “[...] they contain $7,740 \pm 1,940 \text{ km}^3$ (or Gigaton; Gt) of ice, sufficient to raise global sea level by $1.7 \pm 0.5 \text{ cm}$ if totally melted²”.

14) Line 21-22: again, the peak is not necessarily important, but how much area is below a certain elevation. E.g. at what elevation is X % of the area in these different regions. To reflect this, we added L21-22 as: “About 60% of the total glacier area of Svalbard is located below that hypsometry peak.”.

15) Line 28 Terminology: SMB strictly speaking only refers to the surface balance (which ablation stakes measure) and not refreezing. The latter is included in the ‘climatic mass balance’. Here it is the climatic balance. See our response to general comment #1.

16) Line 49: vague: what kind of ‘future warmer climate’. We meant if climate warming continues at the current rate. We reformulated L63-65 as: “The subsequent loss of refreezing capacity, i.e. the fraction of rain and meltwater retained or refrozen in firn (see Methods), implies that Svalbard ice caps can no longer be sustained when the current climate persists or further warming occurs.”

17) Line 52/53: remove “yellow stars” and “in the ablation (blue)”. This holds for other places in the manuscript as well. Please remove any reference to colors or symbols in the main text – this should only be in the captions. Just refer to the appropriate figure. We modified the manuscript accordingly.

18) Line 53: what time periods do these 1611 measurements cover: are they annual balances, winter, summer, other periods? We used 1,611 annual balance measurements covering the period 1967-2015. We reformulated L67-69 as: “The SMB product is evaluated using 1,611 local (in situ) annual balance measurements from 101 sites (Fig. 1a) collected in the ablation and accumulation zones of Svalbard glaciers over the period 1967-2015 (see Methods; Fig. S2a).” and described the in situ sites and measurements in the Method section in L232-238 as: “We use 1,611 local (in situ) annual balance measurements covering the period 1967-2015 and collected at 101 sites (Fig. 1a) on Austre Brøggerbreen, Midtre Lovénbreen, Kongsvegen and Holtedahlfonna glaciers in NW Svalbard ^{42, 43}; Hansbreen glacier in SS sector ⁴⁴; Austfonna ice cap ²² and Nordenskiöldbreen glacier in NE Svalbard ⁴⁵. Stake annual balance is estimated as the elevation difference between two consecutive end-of-summer surface heights (September). For a meaningful comparison, modelled SMB was integrated between September 15 of two consecutive years.”. Appropriate references to the data sets have also been inserted accordingly.

19) Line 59 after “Fig 1a” to line 61: remove. The caption /figure shows these sectors. For clarity, we prefer listing each sector and their acronym once, as they will be heavily used in the Ablation zone and firn line reread and Discussion sections. We rephrased L79-81 as: “To that end, we divide Svalbard in six sectors (Fig. 1a) namely Northwest (NW), Northeast (NE), Vestfonna (VF), Austfonna (AF), Barentsøya and Edgeøya (BE), and South Spitsbergen (SS).”.

20) Line 75: I assume the authors mean ‘net mass loss’ since mass loss happens every year even in years with positive mass balance. Indeed, thank you this is corrected.

21) Line 79: ‘confirms the large fluctuations’: it is unclear what it confirms? Has this result been found by others and published and here your model comes up with the same result? ‘Confirms’ is related to observed remotely sensed mass changes. This is now clarified in L100-102 as: “Both remote sensing data and our reconstruction show that Svalbard glaciers have experienced mass loss since the mid-1980s, including the pause between 2005-2012.”.

22) Line 88, not sure if ‘mitigating’ is the right word here. We replaced by “reducing”.

23) Line 98: why +62% this is unclear. We agree that this is confusing and removed it altogether.

24) Line 102: decline should be change if negative numbers follow. We reformulated L124 as: “[...] similar decline in refreezing capacity, ranging from 22% in NW to 36% in BE sectors”.

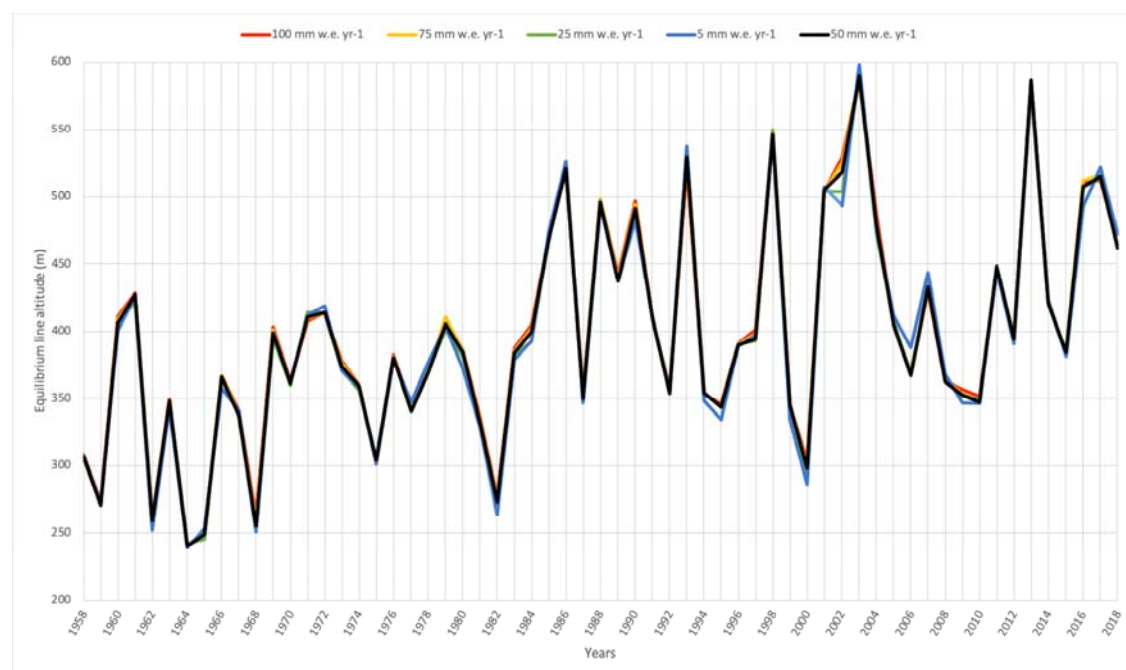
25) Line 161: remove ‘In brief’. Done.

26) Methods: how is firn extent modeled? The firn line corresponds to the interface between the

accumulation and ablation zone (i.e. ELA). The firn area is defined as the accumulation zone area, i.e. the residual of the ablation zone area listed in Tables S2 and S3. This is clarified in L230-231: “The ablation zone area is calculated as the area below the ELA, whereas the firn area coincides with the accumulation zone area above the ELA.”.

27) 40 snow layers: how deep are subsurface processes modeled and how deep is the firn in Svalbard? The snow layer in RACMO2 can be as deep as 30 to 40 m in Svalbard. This is now clarified in L198 as: “In RACMO2.3 Svalbard firn can be 30 to 40 m deep locally.”.

28) Modelled ELA: the method is unorthodox and can lead to very different results than when done as typically done, i.e. estimated from the mass balance gradient (where it's zero). Esp when ELAs are not rather straight lines, deviations can be large. To ensure that our method realistically samples the evolution of the ELA (and its uncertainty) for individual glaciers and Svalbard-wide, we repeated the procedure using different thresholds i.e. ± 5 , ± 25 , ± 75 and ± 100 mm w.e. yr^{-1} . We obtained very similar results (see Figure below). The threshold of ± 50 mm w.e. yr^{-1} was selected as a trade-off between sufficient available pixels to estimate the ELA and a relatively low SMB threshold to avoid overestimation (threshold > 50 mm w.e.) / underestimation (threshold < 50 mm w.e.) of the ELA. A maximum height difference of 25 m is obtained for the 5 mm w.e. yr^{-1} threshold in 2002, which is significantly less than the estimated uncertainty of 80 m i.e. 1 standard deviation of the period 1985-2018. This is now clarified in L227-230 as: “We repeated the procedure using various thresholds ranging from 5 to 100 mm w.e. and obtained very similar results with a maximum ELA difference of 25 m in year 2002, well below the estimated uncertainty of 80 m (1985-2018; Table S3)”.



29) Line 157: bold statement without any evidence? Where does this come from? We used the “modelled” mass loss rate of the period 2013-2018 of $19.4 \pm 3.4 \text{ Gt yr}^{-1}$, i.e. SMB (-8.4 Gt yr^{-1}) minus calving from combined Blaszczyk et al. (2009; 6.8 Gt yr^{-1}) and Dunse et al. (2015; 4.2 Gt yr^{-1}), and the previous ice volume estimates of $5200\text{-}7300 \text{ km}^3$ (or Gt) from Fürst et al. (2018) to derive an early-late timing of Svalbard deglaciation. Early estimate of $5200/19.4 = 268$ or about 250 years; late estimate of $7300/19.4 = 376$ or about 400 years. Using the updated estimate of Farinotti et al. (2019), we obtain: $7470/19.4 = 385$ or approximately 400 years. This is now updated in L175-177 as: “At the current mass loss rate ($19.4 \pm 3.4 \text{ Gt yr}^{-1}$ for 2013-2018), Svalbard glaciers would completely melt within the next 400 years.”

30) Overall a number of figure captions should be improved (I give some examples below). Often the first line reads like a campaign slogan. Best just to state what is shown rather than a ‘conclusion like

statement', e.g. 'Strong sensitivity ...' We modified the caption of Fig. 2 as: "Cumulative mass change of Svalbard glaciers and contribution to sea level rise."; Fig. 3 as: "Ablation zone expansion and reduced refreezing capacity."; Fig. 4 as: "Sensitivity of Svalbard refreezing capacity to atmospheric warming."; Fig. 5 as: "Ablation zone expansion in summer 2013."; Fig. S2 as: "Model evaluation using in situ and remote sensing measurements."; Fig. S4 as: "Ablation zone expansion and runoff change."; Table S1 as: "Model evaluation using recent mass change estimates."

Also when there is a legend the colors of lines etc don't need to be repeated in the caption. Many caption can be shortened and thus become better readable. We modified the captions accordingly.

Comments on Figures:

31) Figure 1: a) color scale: would be better to reverse with positive numbers at top. Done. b) yellow stars are almost impossible to see and the shape not at all. Perhaps just dots and a more distinguishable color. We now use orange dots. c) remove acronyms for plot b. They are not necessary and only make this figure hard to grasp – there is lots of space to spell out each region. GrIS: Greenland ice sheet, GIC: Greenland periphery or Greenland glaciers; NCAA: S Canadian Archipelago ... (the domain is clear from the map, 'Arctic' not needed). Same for Svalbard map, the full region names could be spelled out. Done. d) the inset map may be easier to read if it had a box. This was removed following reviewer #1's suggestions.

32) Figure 1 caption: a) add 'modeled' to caption in first line. Done. b) 'elevation level': is this elevation band? Binning interval needs to be stated. This was revised following reviewer #1's comment as: "The x-axis shows the glacier area in each 100 m elevation band as a fraction of the total ice area of that region (%)."

33) Figure 2: a) colors don't need to be repeated in the caption, there is a legend. Done. b) legend is a bit confusing since all is mass balance, i.e. some form of mass change; and it's not immediately clear that there are 3 components shown based on this study and 3 sets of observational data sets. Perhaps the legend can be split into two columns? Done. c) green for both ICESat and CryoSat is not well visible. For clarity, ICESat data are now shown in light blue. This also holds for Fig. S2c. d) A color scheme suitable for color-blind people should be chosen. We deem that the palette used is sufficiently clear and contrasted. In addition, these colours are consistent with our previous publications e.g. Noël et al. (2017). e) the Discharge curve is misleading since it looks like it is a mass gain (negative sea level rise). The problem is the lack of consistency in sign convention (gain +, losses -). This convention is followed for all curves but D. This needs to be fixed somehow best with using consistent sign convention, i.e. the D curve becomes a negative mass change. As mentioned in the caption, only the "reconstructed mass balance" (MB) is converted into sea level rise equivalent. As D cannot be negative, our use of signs is physically consistent: SMB and D are both positive, only mass balance becomes negative as $MB = SMB - D$: "The right y-axis translates Svalbard cumulative mass balance into global sea level rise equivalent.". In addition, showing D as negative would make the figure more confusing, with 5 different time series (MB, D, GRACE, ICESat, CryoSat-2) confined in the lower part of the graph. In line with our previous work (e.g. Van den Broeke et al., 2016; The Cryosphere), we decided to leave it as is. f) Caption better: Modeled and observed mass changes and contr. ... Not clear why 'Onset', it shows more than that. We reformulated as: "Cumulative mass change of Svalbard glaciers and contribution to sea level rise.". a) add 'modeled': Time series of modeled ... We reformulated as: "Time series of monthly cumulative modelled SMB, measured cumulative solid ice discharge (D)^{11,12} and reconstructed cumulative mass balance (MB = SMB minus D) for the period 1958-2018. Observed mass change derived from GRACE (2002-2016), ICESat (2003-2009) and CryoSat-2 (2010-2018) are also shown.". b) It's unclear why the right y-axis is only for the post-1985 mass loss. Doesn't the translation hold for the entire period? Indeed, we reformulated as: "[...] reconstructed cumulative mass balance (MB = SMB minus D) for the period 1958-2018."

34) Figure 3: a) spell out acronyms. There is enough space. Done. b) caption: remove 'irreversible'. Done. c) caption: remove 'cumulative', it's not cumulative but the rate. Done. d) plot c: replace 'Integrated area' by Area. Done. e) plot c: the legend is confusing. Better (e.g. in 3 rows): Modeled ablation area, Modeled bare ice area, Observed bare ice area (MODIS). Done. It would be useful if Figure 3a (main text) could also be expressed in specific units for comparison with mass change rates in other regions/studies. If the area was constant throughout the time period this could just be added

as a second y-axis. If not perhaps another figure in the supplementary? [As suggested, we now include a second y-axis converting Gt yr⁻¹ into m w.e. yr⁻¹.](#)

35) Figure 4 a) Remove JJA from axis label and put in caption: .. (a) 2 m summer (JJA) air temperature anomaly and ELA. [Done.](#) (b) remove 'change' also all other variables, just give the variable and no direction of change. [This was corrected accordingly.](#)

Supplementary material

Figure S1: scale or coordinates missing. [Scale added.](#)

Figure S2: a) Plot a: y-axis label: remove Downscaled and at 0.5 km, that can be in the caption. [We prefer keeping the label as is for clarity.](#) b) Caption: Evaluation of what? [We reformulated as: "Model evaluation \[...\]"](#). c) Plot c: legend is confusing. All is mass balance, the difference is that the blue is modeled: replace 'Mass balance' by 'Modeled'. [The mass balance is not "stricto sensu" modelled since it is estimated as the difference between modelled SMB and measured Discharge. We reformulated as: "reconstructed mass balance"](#). d) Plot b: there should some sort of multiplication symbol between the bias/rmse numbers and the 10³. [Done.](#) e) Plot b: spell out legend acronyms; there is sufficient space. [Done.](#)

Figure S3: a) The acronyms are not needed and should be spelled out for easier readability. [Done.](#)

Figure S4: a) The caption: upward migration of the ELA seems misleading. I see the SMB and runoff change but no migration? [We rephrased as: "Ablation zone expansion and runoff change."](#) b) The ELA for the 2 periods is not readable. [Given the shape and size of Svalbard glaciers we could not improve the representation of the ELAs and left these as were. We deem that major ELA changes are well visible.](#) c) For clarity: 1985-2018 would be better in legend. [Done.](#)

Supple Table 1 a) Comparison of what? Comparison of modeled and recent estimates. [We reformulated as: "Model evaluation \[...\]"](#). b) Explain PDD and EBM in caption, also WRF and MAR. [Done.](#)

Supple Table 2 a) What's cap? How is it defined? The decimals seems not warranted, same for Ablation area. [We replaced "cap." by "capacity" and kept the decimals.](#) b) What are the uncertainties for ELA? [As mentioned in the Methods, ELA uncertainty is estimated as one standard deviation of the Svalbard-wide ELA \(or individual sectors\) for each period i.e. 1958-1984 and 1985-2018. This is now clarified in the caption as: "ELA uncertainty is estimated as one standard deviation of the period 1958-1984."](#) c) It might be better to call the ice masses just glaciers instead of ice caps, since I assume the table includes not only those ice masses that are from a morphological point an ice cap? [We agree and reformulated accordingly, thank you!](#)

Low elevation of Svalbard glaciers drives high mass loss variability

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**1 Compared to other Arctic ice masses, Svalbard glaciers are low-elevated with flat interior
2 accumulation areas, resulting in a marked peak in their current hypsometry (area-elevation
3 distribution) at ~450 m above sea level. Since summer melt consistently exceeds winter snow-
4 fall, these low-lying glaciers can only survive by refreezing a considerable fraction of surface
5 melt and rain in the porous firn layer covering their accumulation zones. We use a high-
6 resolution climate model to show that modest atmospheric warming in the mid-1980s forced
7 the firn zone to retreat upward by ~100 m to coincide with the hypsometry peak. This led to
8 a rapid areal reduction of firn cover available for refreezing, and strongly increased runoff
9 from dark, bare ice areas, amplifying mass loss from all elevations. As the firn line fluctuates
10 around the hypsometry peak in the current climate, Svalbard glaciers will continue to lose
11 mass and show high sensitivity to temperature perturbations.**

12 Glaciers and ice caps in the Svalbard archipelago (Fig. 1 a) cover an area of ~34,000 km², rep-
13 resenting about 6% of the world's glacier area outside the Greenland and Antarctic ice sheets ¹;
14 they contain $7,740 \pm 1,940$ km³ (or Gigaton; Gt) of ice, sufficient to raise global sea level by 1.7
15 ± 0.5 cm if totally melted ². As a result of Arctic Amplification ³, in which Arctic warming over
16 the last two decades was twice the global average ⁴, and being situated at the edge of retreating
17 Arctic sea ice, Svalbard ice caps experience among the fastest warming on Earth. Compared to
18 other Arctic ice caps, Svalbard glaciers have relatively low elevations (Fig. 1b). The highest ele-
19 vation on Svalbard is approximately 1,700 m a.s.l. (above sea level), but the glacier hypsometry
20 (area-elevation distribution) peaks at ~450 m a.s.l. compared to 800-1,400 m a.s.l. for ice caps in
21 Greenland, Arctic Canada and Iceland (Fig. 1b). About 60% of the total glacier area of Svalbard
22 is located below that hypsometry peak. Moreover, Svalbard ice caps have relatively flat interior
23 accumulation zones leading to a more pronounced peak compared to other Arctic ice masses (Fig.
24 1b).

25 Combined in situ and remote sensing measurements show that Svalbard land ice has been losing

26 mass at strongly fluctuating rates since the early 2000s ^{1,5-12}. According to Gravity Recovery And
27 Climate Experiment (GRACE) data, mass loss virtually stopped in 2005-2012, between two peri-
28 ods of sustained mass loss (2002-2004 and 2013-2016) ¹⁰. **Glacial mass balance (MB) expresses**
29 **the difference between the surface mass balance (SMB) and solid ice discharge (D). Glacial mass**
30 **loss can thus originate from increased D from accelerating marine-terminating glaciers ¹³, and/or**
31 **a decrease in SMB, the difference between mass accumulation from snowfall and ablation mainly**
32 **from meltwater runoff. Surge-type glaciers strongly impact D and are widespread in Svalbard ¹⁴,**
33 **with more than 700 glaciers that likely surged in the past ¹⁵. Although surge events can strongly in-**
34 **fluence mass loss locally ¹⁶, these events are poorly understood and are only documented for a few**
35 **glaciers ¹⁷⁻¹⁹. Here we use a Svalbard-wide solid ice discharge estimate for the period 2000-2006**
36 **¹³, complemented by an increase in D after the surge of a major Austfonna glacier in 2012-2013**
37 **²⁰.**

38 While ice discharge can be derived from remote sensing, surface processes driving the SMB of
39 Svalbard glaciers remain poorly constrained. Regional climate models can, in principle, **represent**
40 **the SMB of Svalbard glaciers ^{21,22}, including internal accumulation of rain and meltwater in firn**
41 **through refreezing (see Methods). However,** these models currently operate at relatively coarse
42 spatial resolutions, typically 5 to 20 km, and do not resolve the narrow marginal ablation zones
43 and outlet glaciers ^{23,24}. In previous studies, **regional climate model** outputs were refined to higher
44 spatial resolution, e.g. 250 m to 1 km, using Positive Degree Day ²⁵ or Energy Balance Models
45 ^{26,27} to show that Svalbard recently lost mass following **an increase in summer ablation (Table S1).**
46 **Similar conclusions were drawn by upscaling in situ SMB measurements to all Svalbard land ice**
47 **¹², but little remains known about the temporal and spatial variability of the surface mass loss.**

48 Statistical downscaling to (sub-)km horizontal resolution ²⁸ is a powerful tool to realistically repre-
49 sent the steep SMB gradients in the topographically complex terrain that characterises the Svalbard
50 archipelago. Here we present and evaluate a new, high-resolution **daily** SMB data set for Svalbard
51 covering the period 1958-2018 (Fig. 1a). SMB components are statistically downscaled from
52 the output of the Regional Atmospheric Climate Model (RACMO2.3) at 11 km resolution ²⁹ to a
53 glacier mask and digital elevation model (DEM) on a 500 m horizontal grid (Fig. S1). **The method**
54 **primarily corrects daily melt and runoff for elevation biases on the relatively coarse RACMO2.3**
55 **model grid using elevation gradients, and for underestimated ice albedo using remote sensing mea-**
56 **surements ²⁸ (see Methods). The new product includes all individual SMB components (snowfall,**
57 **rainfall, sublimation, melt, refreezing and runoff) required to identify the drivers of the recent sur-**
58 **face mass loss and its variability. Combined with discharge estimates ^{13,20}, our high-resolution**
59 **SMB product enables us to estimate the spatially and temporally varying mass balance of Svalbard**
60 **glaciers over the last six decades, including the high mass loss variability starting in the mid-1980s.**
61 We show that a modest atmospheric warming of 0.5°C in the mid-1980s was sufficient to raise the
62 firn line to the hypsometry peak at ~450 m a.s.l., exposing large parts of the accumulation area to
63 increased melt. The subsequent loss of refreezing capacity, i.e. the fraction of rain and meltwater
64 retained or refrozen in firn (see Methods), implies that **Svalbard ice caps** can no longer be sustained
65 **when the current climate persists or further warming occurs.**

66 Results

67 **Model evaluation.** The SMB product is evaluated using 1,611 local (in situ) annual balance mea-
68 surements from 101 sites (Fig. 1a) collected in the ablation and accumulation zones of Svalbard
69 glaciers over the period 1967-2015 (see Methods; Fig. S2a). Good agreement with the SMB prod-
70 uct is found ($R^2 = 0.63$), with a small positive bias of 5 mm w.e. yr^{-1} (water equivalent). Note
71 that significant deviations (RMSE) of up to 440 mm w.e. yr^{-1} remain locally (Fig. S2a). Un-
72 like the downscaled SMB product, stake measurements in the accumulation zone do not include
73 internal accumulation from the refreezing of melt and rain (see Methods). Ignoring internal ac-
74 cumulation when comparing the model to stake measurements located in the accumulation zone
75 leads to a small RMSE increase of ~ 50 mm w.e. yr^{-1} . We estimate an uncertainty in total Sval-
76 bard SMB of 1.6 Gt yr^{-1} ($\sim 25\%$) for the period 1958-2018 (see Methods). Using data from the
77 Moderate Resolution Imaging Spectroradiometer (MODIS) satellite over 2000-2018, we also eval-
78 uate the modelled bare ice area, i.e. the part of the ablation zone where bare ice is exposed after
79 the seasonal snow has melted (Fig. S2b). To that end, we divide Svalbard in six sectors (Fig.
80 1a) namely Northwest (NW), Northeast (NE), Vestfonna (VF), Austfonna (AF), Barentsøya and
81 Edgeøya (BE), and South Spitsbergen (SS). With 93% of the variance explained and an average
82 negative bias of 90 km^2 , modelled and observed bare ice area compare very well (Fig. S2b).

83 We assume that solid ice discharge estimate for 2000-2006 ($D = 6.8 \pm 1.8 \text{ Gt yr}^{-1}$)¹³ is valid
84 for the whole study period (1958-2018). In line with Dunse et al. (2015)²⁰, we increase solid
85 ice discharge by $4.2 \pm 1.6 \text{ Gt yr}^{-1}$ from 2012 onwards, following the surge of a major Austfonna
86 outlet glacier. Combining this with the downscaled SMB product, we reconstruct the mass change
87 of Svalbard glaciers over the last six decades (Fig. 2). The modelled mass change is obtained by
88 integrating both SMB and D in time starting from zero in 1958. Our reconstruction agrees very
89 well with remote sensing records from GRACE (2002-2016)¹⁰ and ICESat/CryoSat-2 altimetry
90 (2003-2018) with $R^2 = 0.93$ and 0.98 , respectively (Fig. S2c). Not only the recent mass trends
91 but also the seasonal and interannual variability are accurately reproduced. Table S1 compares our
92 results to other mass change estimates derived from geodetic techniques^{1,11}, GRACE^{5-8,10}, SMB
93 models including a Positive Degree Day²⁵, two Energy Balance Models^{26,27} and two regional
94 climate models^{21,22}, and in situ measurements¹².

95 **Recent mass loss onset.** Our reconstruction shows that Svalbard glaciers remained in approximate
96 balance ($\text{SMB} \approx D$) until the mid-1980s (Fig. 2), i.e. the surface mass gain compensates the
97 dynamic mass loss from calving¹³. Net mass loss starts around 1985, primarily due to a persistent
98 SMB decrease, reinforced from 2012 onwards by enhanced ice discharge²⁰, but with a mass loss
99 pause between 2005 and 2012. Our reconstruction suggests that Svalbard has lost $\sim 350 \text{ Gt}$ of ice
100 since 1985, contributing $\sim 1 \text{ mm}$ to global sea level rise (Fig. 2). Both remote sensing data and
101 our reconstruction show that Svalbard glaciers have experienced mass loss since the mid-1980s,
102 including the pause between 2005-2012. Understanding the drivers of the pronounced post-1985
103 mass loss variability requires investigating spatial and temporal fluctuations in individual SMB
104 components.

105 **Ablation zone expansion and firn line retreat.** Figure 3a shows time series of individual SMB
106 components covering the period 1958-2018. The ice caps of Svalbard experience average summer
107 melt (1958-1984 average of 28.7 Gt yr^{-1} , Table S2) that exceeds annual **total precipitation** (23.0
108 Gt yr^{-1} including rain and snow) by 25%. This proves that retention of surface meltwater in the
109 firn through refreezing is crucial to sustain these ice caps. The refreezing capacity is defined as
110 the fraction of liquid water (melt and rain) that is retained in the firn. Before 1985, the refreezing
111 capacity was 54%, reducing meltwater runoff (16.3 Gt yr^{-1}) and resulting in a positive SMB (6.3
112 $\pm 1.6 \text{ Gt yr}^{-1}$; Fig. 3a). This surface mass gain was almost exactly offset by solid ice discharge
113 ($6.8 \pm 1.8 \text{ Gt yr}^{-1}$)¹³.

114 Following a modest atmospheric warming ($+0.5^\circ\text{C}$; 1985-2018 minus 1958-1984), the **average**
115 equilibrium line altitude (ELA; local SMB = 0) **moved** upwards by ~ 100 m, from ~ 350 m a.s.l. to
116 ~ 450 m a.s.l. (Fig. 3b). The orange band in Fig. 3b spans the six regional ELA **values, the change**
117 ranging from $+80$ m in SS to $+130$ m in the NE sectors (Tables S2 and S3). The ELA increase
118 caused a rapid retreat of the firn line, **as shown** by the post-1985 growth of the bare ice zone
119 ($+75\%$; Fig. 3c) in good agreement with MODIS records (see Methods). As a result, the ablation
120 zone expanded from 27% to 44% of the total glacier area (Fig. 3c). While **total precipitation** did not
121 significantly change after 1985 (-1%), surface melt increased by 24%, exceeding accumulation by
122 58%, while the refreezing capacity declined from 54% (1958-1984) to 40% (1985-2018; Fig. 3d).
123 The blue band in Fig. 3d spans the six individual regions that underwent a simultaneous and similar
124 decline in refreezing capacity, **ranging from 22% in NW to 36% in BE sectors**, respectively (Tables
125 S2 and S3). Consequently, SMB became predominantly negative ($-2.6 \pm 1.6 \text{ Gt yr}^{-1}$), initiating
126 the post-1985 mass loss of Svalbard glaciers. We conclude that all regions in Svalbard experienced
127 rapid ablation zone expansion and reduced firn refreezing capacity, resulting in strongly increased
128 meltwater runoff ($+55\%$), driving the post-1985 glacial mass loss ($\text{MB} = -10.2 \pm 3.4 \text{ Gt yr}^{-1}$;
129 Table S3).

130 **Discussion** Compared to other Arctic ice masses^{23,24}, Svalbard glaciers have a low elevation and
131 are relatively flat **with a marked hypsometry peak at ~ 450 m a.s.l.** (Fig. 1b). Before 1985,
132 the ELA was at 350 ± 60 m a.s.l., well below the hypsometry peak (Figs. 1, 3b and S3a). In
133 this period, 70% of the total **glacier** area was covered with extensive firn zones, in which most
134 meltwater and rain were refrozen. This kept the SMB positive, as runoff remained smaller than
135 **snow accumulation** (Fig. 3a). Following a modest atmospheric warming after 1985, the ELA
136 moved upward by ~ 100 m to 440 ± 80 m a.s.l. (Figs. 3b and S3b), nearly coinciding with the
137 hypsometry peak (Fig. S3d). This rapidly expanded the ablation zone, exposing large areas to
138 increased melt. The subsequent firn line retreat strongly reduced the fraction of melt that refreezes
139 above the pre-1985 ELA (Fig. 3d), enhancing runoff 75% faster than melt ($+8.9 \text{ Gt yr}^{-1}$ vs $+6.7$
140 Gt yr^{-1}). Figure S4a shows the ELA change across Svalbard as a result of the post-1985 warming
141 ($R = 0.82$; Fig. 4a). The ablation zone extent increases non-linearly with the upward migration
142 of the ELA (Fig. 4b), reflecting the proximity of the hypsometry peak (Figs. 3b, c). The size
143 of the ablation zone in turn governs meltwater production (Fig. 4c), since most of the melt is
144 produced over low-lying marginal glaciers exposing dark bare ice (Fig. S4b). In the absence of

145 refreezing, the low albedo of exposed ice increases melt through enhanced absorption of incoming
146 solar radiation, in turn driving the runoff increase. Most remarkably, increased melt triggers a
147 pronounced non-linear decrease in refreezing capacity (Fig. 4d), as i) the firn line retreat strongly
148 reduces the firn area hence limiting meltwater retention, and ii) meltwater fills the pore space of
149 the remaining firn through refreezing. These mechanisms could likely be reinforced by increased
150 rainfall episodes in a warmer climate, further reducing firn refreezing capacity³⁰.

151 Regionally, the upward migration of the ELA is largest in the northernmost sectors, e.g. NE (+130
152 m) and AF (+120 m), compared to southern sectors with an average of +85 m (Tables S2 and S3).
153 As a result, the ablation zone also grew fastest in the north, e.g. NE (+73%), VF (+91%) and
154 notably AF (+137%; Fig. S4a) compared to southern sectors (+48% on average; Tables S2 and
155 S3). For the northern sectors, this resulted in a 66% to 71% runoff increase after 1985, i.e. well
156 above the Svalbard average (+55%; Tables S2 and S3). These three northernmost sectors exhibit a
157 stronger response to atmospheric warming because of a pronounced decline in refreezing capacity
158 across their accumulation zones (-40% locally; Figs. 4d, e), increasing runoff at all elevations (Fig.
159 S4b). These results are in line with the study of Van Pelt et al. (2019) (see their Fig. 9d)²⁷. Since
160 it has the largest accumulation zone, the strongest sensitivity to atmospheric warming is found for
161 Austfonna ice cap (AF sector), containing a third ($\sim 2,500 \text{ km}^3$)¹⁶ of the total ice volume in the
162 archipelago. In contrast, for regions with smaller accumulation zones (NW and SS) or that had
163 already lost most of their refreezing capacity before 1985 (BE; Table S2), the runoff increase is
164 restricted to the margins (Fig. S4b), and primarily driven by ablation zone expansion rather than
165 loss of refreezing capacity (Fig. 4c).

166 The fact that the ELA now **fluctuates** around the hypsometry maximum makes Svalbard glaciers
167 highly sensitive to changes in atmospheric temperature. During warm summers, the ablation zone
168 now covers more than half of the surface area of most ice caps (Fig. 3c). In the warm summer of
169 2013, the ablation zone even covered 77% of the **land ice** area (Fig. 5b), almost **twice** the post-1985
170 average (44%; Table S3). This pronounced expansion stems from the fact that in 2013 the ELA
171 moved to 590 m a.s.l., i.e. **above** the hypsometry peak (Fig. S3d). Consequently, the refreezing
172 capacity dropped to 28% (2013), more than doubling runoff compared to previous years (47 Gt
173 yr^{-1} ; Fig. 3a). **We conclude that the post-1985 decline in refreezing capacity will persist under**
174 **continued warming:** a temporary return to pre-1985 SMB values in the period 2005-2012 (Figs. 3a
175 and 5a) did not lead to the recovery of the **refreezing capacity** (Fig. 3d). **At the current mass loss**
176 **rate ($19.4 \pm 3.4 \text{ Gt yr}^{-1}$ for 2013-2018), Svalbard glaciers would completely melt within the next**
177 **400 years.**

178 **Methods**

179 **Regional climate model and statistical downscaling.** We use the outputs of the Regional At-
180 mospheric Climate Model (RACMO2.3)²⁹ as input to the statistical downscaling procedure²⁸.
181 RACMO2.3 is run at 11 km spatial resolution for the period 1958-2018. The model incorporates

182 the dynamical core of the High-Resolution Limited Area Model (HIRLAM)³¹ and the physics
 183 of the European Centre for Medium-Range Weather Forecasts-Integrated Forecast (ECMWF-IFS
 184 cycle CY33r1)³². RACMO2.3 includes a multi-layer snow module simulating melt, water per-
 185 colation, retention and refreezing in firm, as well as runoff³³. The model accounts for dry snow
 186 densification³⁴, drifting snow erosion and sublimation³⁵, and explicitly simulates snow albedo
 187 ³⁶. **In this study we refer to 'surface mass balance' (SMB) as both the local (kg m²) and spatially**
 188 **integrated (Gt yr⁻¹) sum of:**

$$\text{SMB} = \text{PR} - \text{RU} - \text{SU} - \text{ER} \quad (1)$$

189 where PR represents total precipitation including snowfall (SF) and rainfall (RA), RU meltwater
 190 runoff, SU total sublimation and ER the erosion from drifting snow. Liquid water from rain and
 191 melt (ME) that is not retained or refrozen in firm (RF) contributes to runoff:

$$\text{RU} = \text{ME} + \text{RA} - \text{RF} \quad (2)$$

192 Note that in Cogley and others (2011)³⁷, the local quantity that includes 'internal accumulation'
 193 from refreezing and retention is referred to as 'climatic mass balance'. Firm refreezing capacity
 194 (RFcap), i.e. the fraction of rain and meltwater effectively retained or refrozen in firm, is estimated
 195 as:

$$\text{RFcap} = \frac{\text{RF}}{\text{ME} + \text{RA}} \quad (3)$$

196 RACMO2.3 is forced by ERA-40 (1958-1978)³⁸ and ERA-Interim (1979-2018)³⁹ reanalyses on
 197 a 6-hourly basis within a 24 grid-cell wide relaxation zone at the 40 vertical atmospheric levels.
 198 **The model also includes 40 active snow layers that are** initialised in September 1957 using vertical
 199 temperature and density profiles derived from the Institute for Marine and Atmospheric research
 200 Utrecht-Firm Densification Model (IMAU-FDM)³⁴. **In RACMO2.3 Svalbard firm can be 30 to 40**
 201 **m deep locally.** Bare ice albedo is prescribed from a down-sampled version of the 500 m MODIS
 202 albedo 16-day product (MCD43A3) as the 5% lowest surface albedo records for the period 2000-
 203 2015, minimised at 0.30 for dark bare ice and maximised at 0.55 for bright ice beneath perennial
 204 firm.

205 To resolve narrow ablation zones and small glaciers of Svalbard, the outputs of RACMO2.3 are
 206 statistically downscaled to a 500 m ice mask derived from the Randolph Glacier Inventory (RGI)
 207 ⁴⁰ version 6.0 and the 20 m spatial resolution S0 Terreng DEM of Svalbard (Norwegian Polar
 208 Institute) down-sampled onto a 500 m grid (Fig. S1). In brief, the downscaling procedure cor-
 209 rects individual SMB components (except for **total precipitation**), i.e. primarily meltwater produc-
 210 tion and runoff, for elevation and ice albedo biases on the relatively coarse model grid at 11 km

211 resolution. These corrections reconstruct individual SMB components on the 500 m topography
212 using daily-specific gradients estimated at 11 km, and minimise the remaining runoff underesti-
213 mation using a down-sampled 500 m MODIS 16-day ice albedo product averaged for 2000-2015
214 (<http://dx.doi.org/10.5067/MODIS/MCD43A3.006>). **Total precipitation**, including snowfall and
215 rainfall, is bilinearly interpolated from the 11 km onto the 500 m grid without additional correc-
216 tions. The statistical downscaling technique is further **described** in Ref. ²⁹.

217 **Product uncertainty.** The SMB uncertainty (σ) is estimated at **an average of** 1.6 Gt yr⁻¹ for the
218 period 1958-2018. The uncertainty is obtained by integrating the conservative 10% and 20% SMB
219 uncertainty in RACMO2.3 ⁴¹ over the accumulation ($A_{\text{accum.}} = 21,100 \text{ km}^2$) and ablation zones ($A_{\text{abla.}}$
220 $= 11,650 \text{ km}^2$) of Svalbard **respectively**. A similar uncertainty is estimated for individual sectors
221 (Tables S2 and S3) following:

$$\sigma = \sqrt{(0.1 \times A_{\text{accum.}})^2 + (0.2 \times A_{\text{abla.}})^2} \quad (4)$$

222 **Modelled ELA.** To estimate the modelled ELA (local SMB = 0), we used the down-sampled S0
223 Terreng DEM of Svalbard at 500 m to average the surface elevation of grid cells showing an annual
224 cumulative SMB ranging from -50 to 50 mm w.e. for each specific year. The procedure was con-
225 ducted separately for the six sectors and the whole of Svalbard over the periods 1958-1984 (Table
226 S2) and 1985-2018 (Table S3). We estimated the associated uncertainty as one standard deviation
227 of the annual ELA for the two periods and for each individual sectors. **We repeated the procedure**
228 **using various thresholds ranging from 5 to 100 mm w.e. and obtained very similar results, with**
229 **a maximum ELA difference of 25 m in year 2002, well below the estimated uncertainty of 80 m**
230 **(1985-2018; Table S3). The ablation zone area is calculated as the area below the ELA, whereas**
231 **the firn area coincides with the accumulation zone area above the ELA.**

232 **Observational data.** We use 1,611 local (in situ) annual balance measurements covering the pe-
233 riod 1967-2015 and collected at 101 sites (Fig. 1a) on Austre Brøggerbreen, Midtre Lovénbreen,
234 Kongsvegen and Holtedahlfonna glaciers in NW Svalbard ^{42,43}; Hansbreen glacier in SS sector
235 ⁴⁴; Austfonna ice cap ²² and Nordenskiöldbreen glacier in NE Svalbard ⁴⁵. Stake annual balance
236 is estimated as the elevation difference between two consecutive end-of-summer surface heights
237 (September). For a meaningful comparison, modelled SMB was integrated between September 15
238 of two consecutive years. The **in situ** data set is made available by the World Glacier Monitoring
239 Service (WGMS) and was compiled by the University of Oslo, the Norwegian Polar Institute, the
240 Polish Academy of Sciences, the University of Uppsala and Utrecht University ²⁷. For consistency,
241 we rejected four sites with > 100 m height difference relative to the S0 Terreng DEM of Svalbard
242 at 500 m spatial resolution. For comparison with stake measurements, we selected the downscaled
243 grid cell with the smallest elevation bias among the closest pixels and its eight adjacent neighbours.

244 **Remotely sensed mass change.** We use a combination of GRACE mass change time series for
245 the period 2002-2016 ¹⁰ with elevation changes derived from ICESat (2003-2009) and CryoSat-2
246 (2010-2018). Following the method described in Refs. ^{7,46}, ICESat records were grouped every 700

247 m along repeated ground tracks, whereas for CryoSat-2, neighbouring observations are collected
248 within 1 km of each individual echo location. A model is fitted to these clusters of elevation
249 observations in order to estimate the local surface topography and elevation rate at the central
250 point, where outliers are removed in an iterative procedure. For full details, we refer the reader
251 to Ref. ⁴⁶. After estimating the local topography and elevation rate for the ICESat and CryoSat-2
252 periods, local elevation anomalies at the echo locations can be estimated by adding the elevation
253 rate of the fitted model to the residuals. These anomalies are used to compute monthly volume
254 anomalies for (individual) Svalbard ice caps. Elevation anomalies are parameterised as a function
255 of absolute elevation using a third-order polynomial. The resulting fit is used to derive regional
256 volume anomalies within 100 m elevation intervals, by multiplying the polynomial value at each
257 interval's midpoint with the total glacier area within this elevation bin ¹. Finally, volume anomalies
258 are converted to mass anomalies by assuming a constant density profile, using the density of ice
259 below the ELA, and a density of $600 \pm 250 \text{ kg m}^{-3}$ above the ELA ⁴⁶.

260 **Bare ice area.** Annual modelled bare ice area is estimated for six sectors and the whole of Sval-
261 bard (Tables S2 and S3) as the area of pixels showing a surface albedo ≤ 0.55 on the 11 km grid,
262 bilinearly interpolated onto the 500 m ice mask, at least 2 days in that year. For comparison,
263 we estimate annual bare ice extent using the broadband shortwave clear sky albedo data from the
264 MCD43A3 MODIS 500-m 16-day albedo product. To eliminate spurious albedo records, erratic
265 albedo grid cells were masked from the MODIS product (2000-2018) using the full Bidirectional
266 Reflectance Distribution Function (BRDF) inversions. Valid MODIS records were classified as
267 bare ice or snow-covered grid cells using an upper threshold for shortwave albedo of 0.55 (i.e.
268 maximum albedo of bright bare ice under perennial firn). Subsequently, bare ice/snow cells were
269 converted to annual bare ice extent if i) the current pixel was classified as ice at least 5 days in that
270 year (5th percentile), ii) the pixel is located within the modelled ablation zone of that year (SMB
271 < 0 ; 2000-2018), and iii) the pixel is located below 700 m a.s.l., which is well above the long-term
272 ELA of Svalbard ($440 \pm 80 \text{ m a.s.l.}$ for 1985-2018) and individual sectors (up to $550 \pm 65 \text{ m}$
273 a.s.l. in NW; Table S3). Even in extremely warm years such as 2003 and 2013, the Svalbard-wide
274 ELA ($600 \pm 80 \text{ m a.s.l.}$; Fig. 3b) remains below the selected elevation threshold. These criteria al-
275 low the elimination of pixels that represent meltwater lakes, superimposed ice and mountain range
276 peaks at higher elevations as often found in the interior of Svalbard. The remaining masked pixels
277 are filled on the basis of ice/snow recurrence for that cell: masked pixels are classified as bare ice
278 if they expose bare ice more than 50% of the time in the period 2000-2018.

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384 **Data availability** Daily downscaled SMB and components at 500 m spatial resolution (1958-2018) and
385 other data required to reproduce the tables and figures presented in the manuscript are available from the
386 authors upon request and without conditions. SMB components include total precipitation (snowfall and
387 rainfall), snowfall, runoff, melt, refreezing and retention, total sublimation and snow drift erosion.

388 **Code availability** RACMO2.3 is presented in Ref. ²⁹ and the statistical downscaling technique is de-
389 scribed in Ref. ²⁸.

390 **Authors contribution** B.N. prepared the manuscript, carried out the RACMO2.3 simulation and produced
391 the downscaled dataset at 500 m. C.L.J. helped conducting and analysing the RACMO2.3 simulations. B.N.,
392 W.J.B. and M.R.B. conceived the downscaling procedure and analysed the data. W.J.J.P., J.K., J.O.H., B.L.
393 and C.H.R. provided the Svalbard in situ SMB dataset and the S0 Terreng DEM. S.L. processed the 500
394 m MODIS albedo product. B.W. produced and analysed the GRACE, ICESat and CryoSat-2 datasets. All
395 authors commented on the manuscript.

396 **Competing Interests** The authors declare that they have no competing financial interests.

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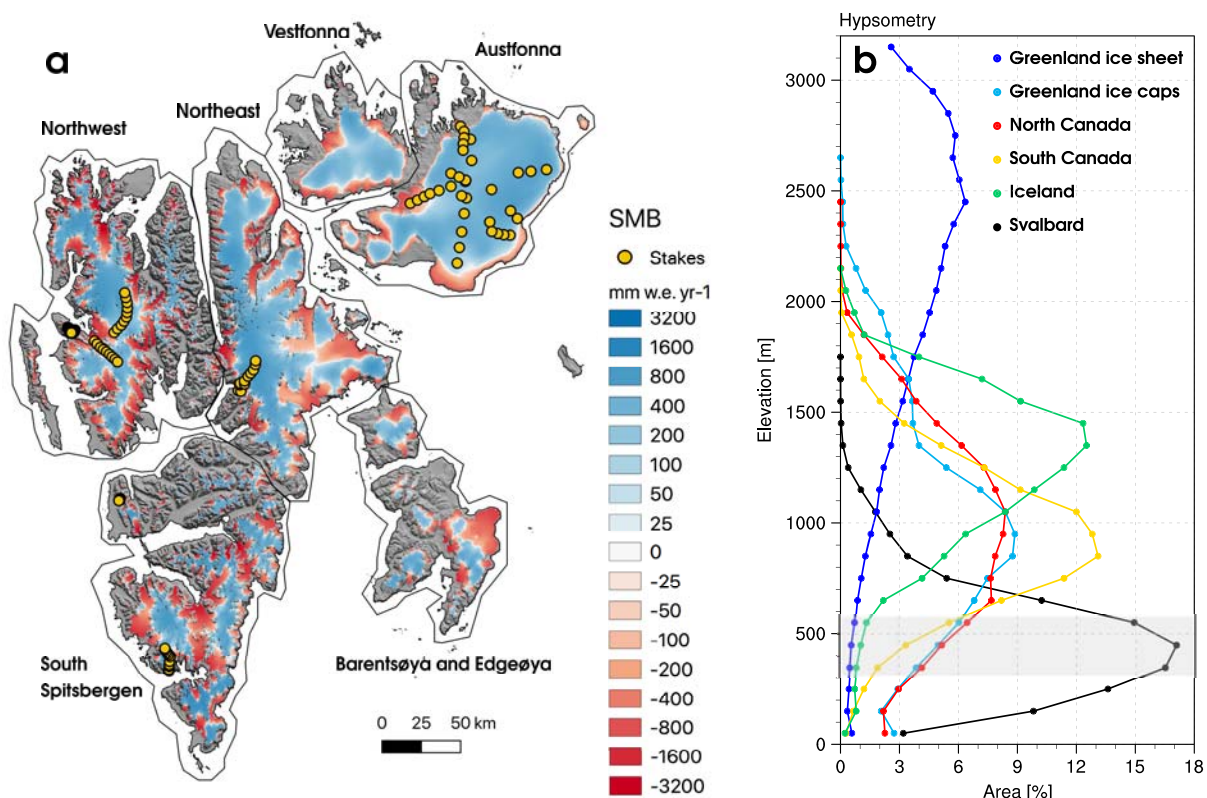


Figure 1: **Svalbard surface mass balance and hypsometry.** (a) **Modelled surface mass balance (SMB) statistically downscaled to 500 m spatial resolution, averaged for the period 1958-2018.** **Orange dots** locate the 101 stakes used for model evaluation (Fig. S2a). The sectors of Svalbard evaluated in Fig. S2b are also outlined. (b) Hypsometry of six Arctic **ice masses**: Svalbard (S0 Terreng DEM), Iceland (Arctic DEM), North and South Canadian Arctic Archipelago (Canadian DEM)²⁴, Greenland ice sheet (GIMP DEM)⁴¹, Greenland peripheral glaciers and ice caps (GIMP DEM)²³. The x-axis shows the **glacier area in each 100 m elevation band** as a fraction of the total ice area of that region (%).

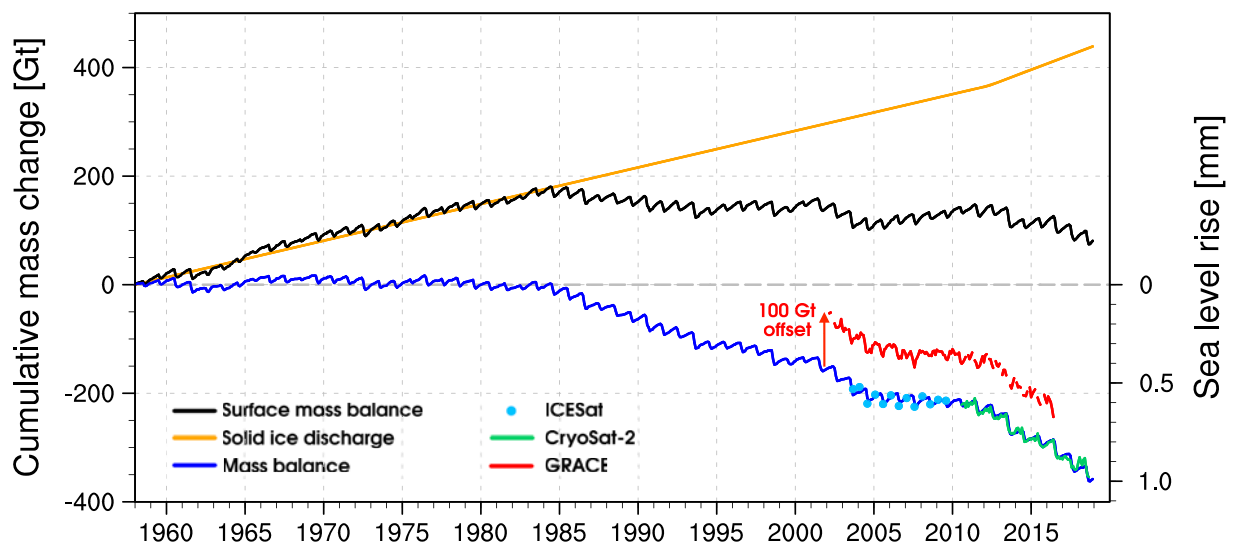


Figure 2: **Cumulative mass change of Svalbard glaciers and contribution to sea level rise.** Time series of monthly cumulative modelled SMB, measured cumulative solid ice discharge (D)^{11,12} and reconstructed cumulative mass balance (MB = SMB minus D) for the period 1958-2018. Observed mass change derived from GRACE (2002-2016), ICESat (2003-2009) and CryoSat-2 (2010-2018) are also shown. For clarity, GRACE data are shown with a positive offset of 100 Gt. The right y-axis translates Svalbard cumulative mass balance into global sea level rise equivalent. Figure S2c zooms in on the satellite period (2003-2018).

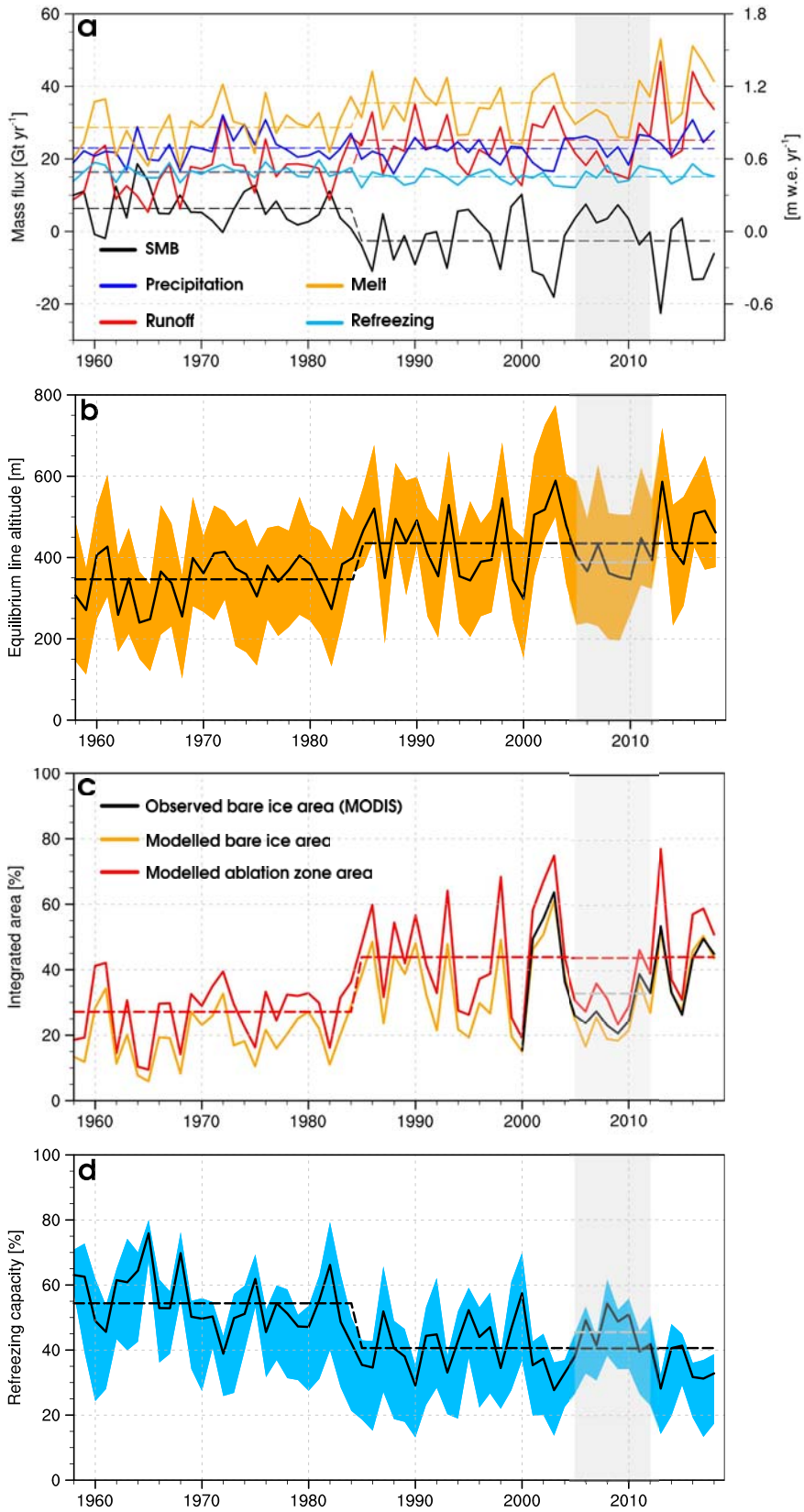


Figure 3: **Ablation zone expansion and reduced refreezing capacity.** (a) Time series of annual SMB and components including surface melt, runoff, **total precipitation** and refreezing for the period 1958-2018. (b) Time series of annual ELA for the whole of Svalbard (black) and individual sectors (Fig. 1a, orange band). (c) Time series showing the modelled ablation zone area, the modelled and observed (MODIS) bare ice area as a fraction of the total Svalbard land ice area (%). (d) Time series of annual refreezing capacity for the whole of Svalbard (black) and individual sectors (cyan band). Dashed lines show averages for the periods 1958-1984 and 1985-2018. The grey shade highlights the period 2005-2012 when Svalbard SMB temporarily returned to the pre-1985 SMB conditions. Dashed grey lines represent the 2005-2012 mean conditions.

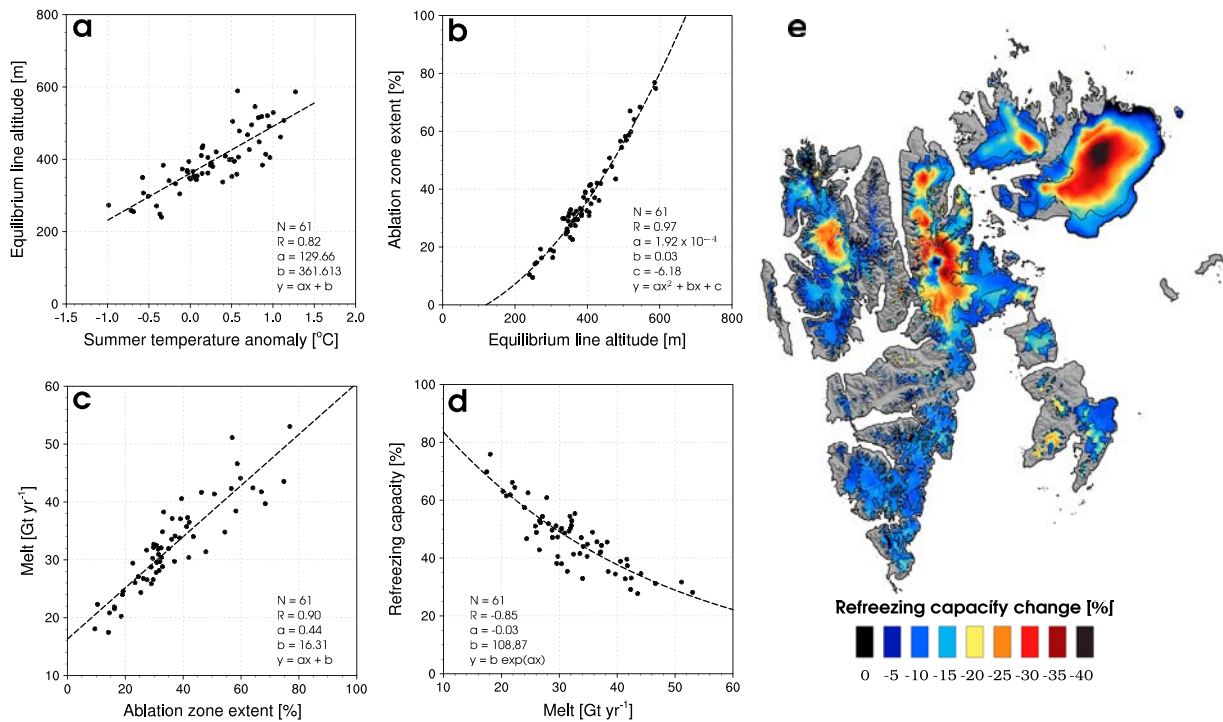


Figure 4: **Sensitivity of Svalbard refreezing capacity to atmospheric warming.** Scatterplots showing Svalbard-wide correlations between (a) **June-July-August 2 m air temperature anomaly (1985-2018 minus 1958-1984)** and ELA; (b) ELA and ablation zone area; (c) ablation zone area and surface melt, and (d) melt and firm refreezing capacity. Statistics include number of records (N), correlation (R) and fitting parameters (a,b,c). (e) Post-1985 change in refreezing capacity (%; 1985-2018 minus 1958-1984). ELA for the period 1985-2018 is also shown as a black line.

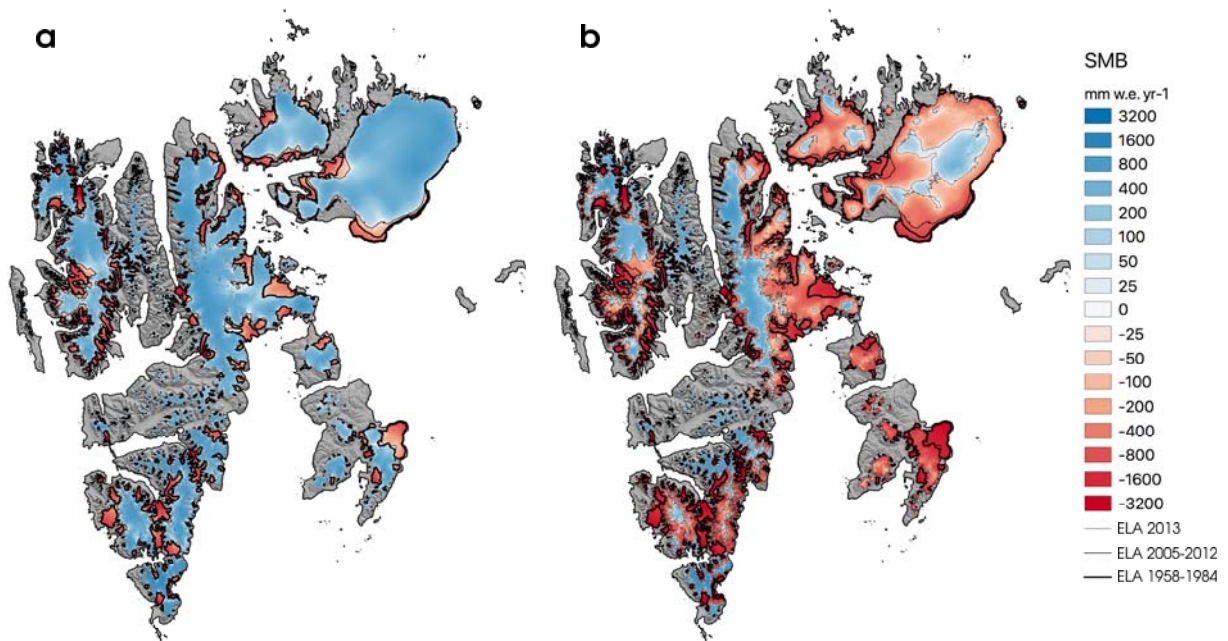


Figure 5: **Ablation zone expansion in summer 2013.** (a) SMB average for the period 2005-2012, with SMB conditions similar to 1958-1984. (b) SMB for year 2013 highlighting how fast the ablation zone expands when the ELA migrates well above the hypsometry maximum (~450 m a.s.l.). From the thickest to the thinnest, black lines outline the ELA for periods 1958-1984, 1985-2018 (a and b) and year 2013 (b only).

Supplementary Information: "Low elevation of Svalbard glaciers drives high mass loss variability"

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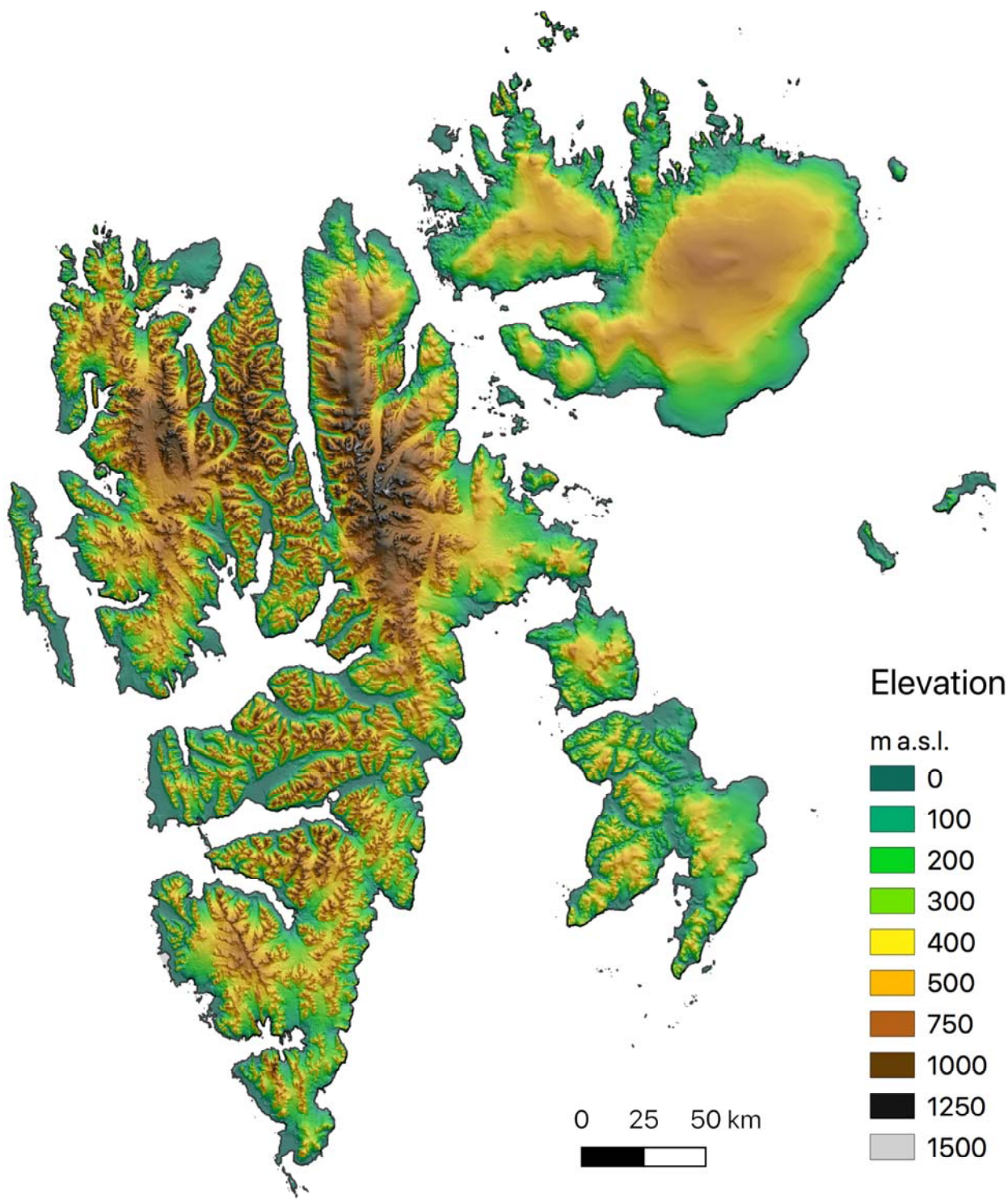
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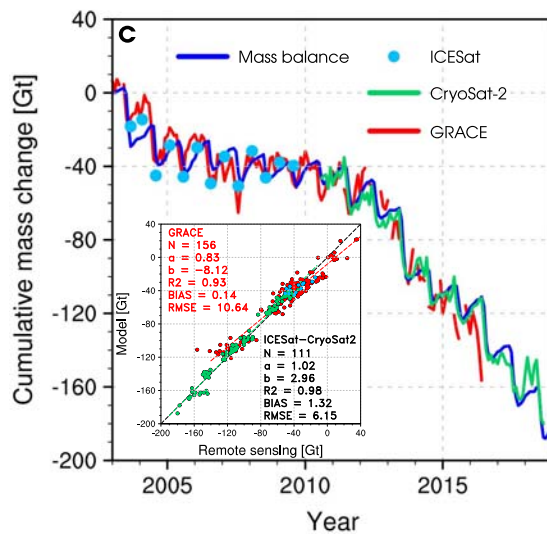
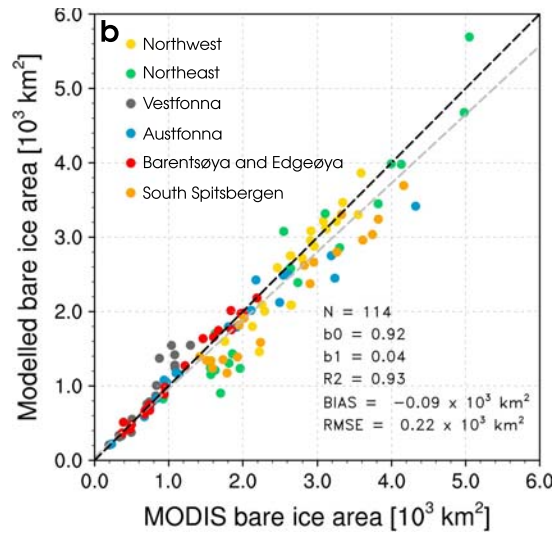
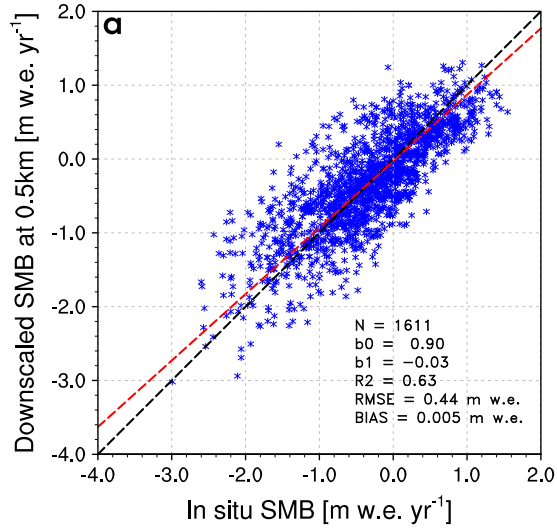
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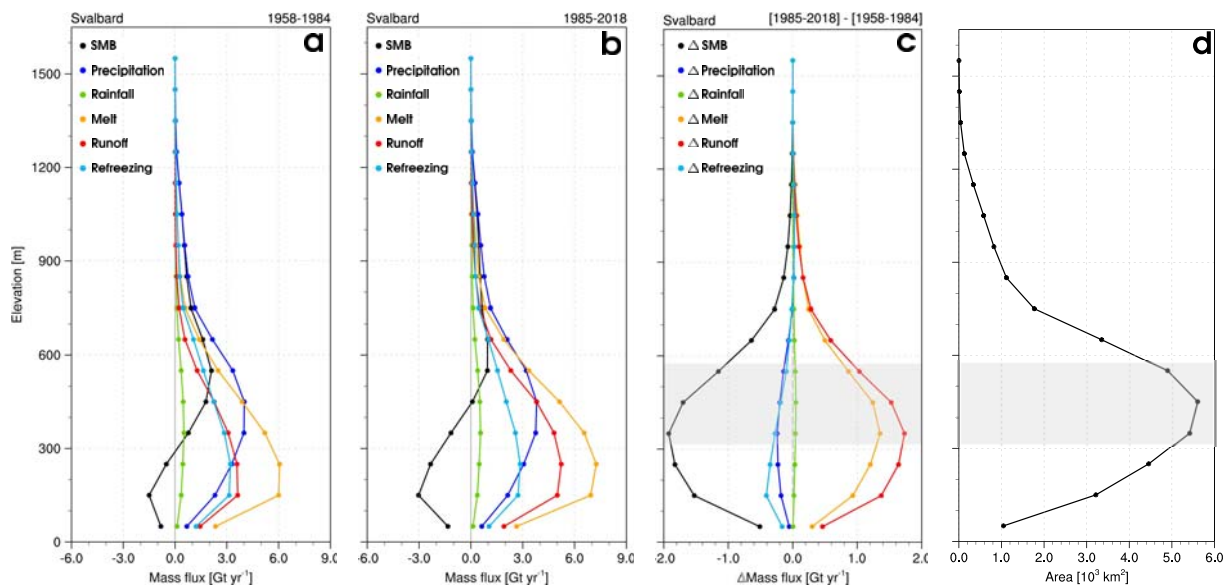
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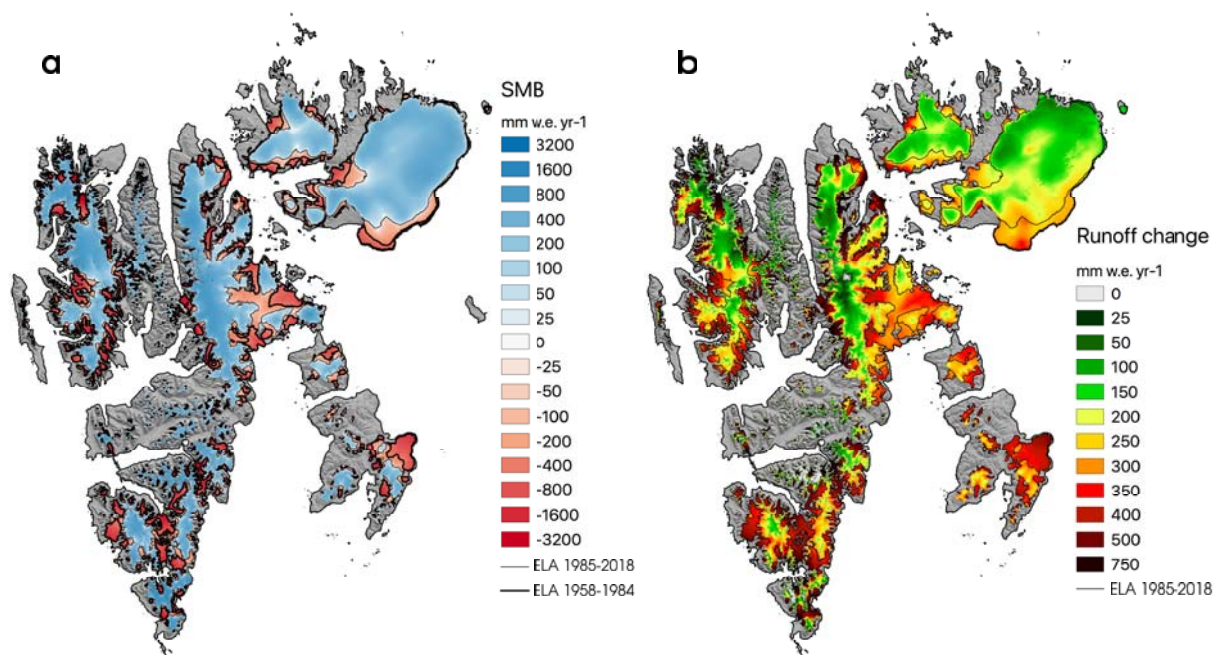
Supplementary Figure 1: **Topography of the Svalbard archipelago.** Surface elevation (m a.s.l.) derived from the S0 Terrenq DEM of Svalbard at 20 m spatial resolution (Norwegian Polar Institute) and down-sampled to a 500 m grid.



Supplementary Figure 2: **Model evaluation using in situ and remote sensing measurements.** (a) Comparison between modelled and observed SMB at 101 stakes (Fig. 1a). The red dashed line represents the regression including all measurements. (b) Comparison between modelled and observed bare ice **area** for individual sectors. The grey dashed line corresponds to the regression using all measurements. (c) Time series of monthly cumulative **reconstructed** mass balance (MB = SMB minus solid ice discharge) overlapping the satellite period (2003-2018): GRACE (2003-2016), ICESat (2003-2009) and CryoSat-2 (2010-2018). The inset in Fig. S2c shows the comparison between modelled and remotely sensed monthly cumulative mass change from GRACE, ICESat and CryoSat-2. Regressions are shown as dashed red (GRACE) and green (ICESat/CryoSat-2) line. Statistics including the number of observations (N), slope (b0) and intercept (b1) of the regression line, coefficient of determination (R^2), RMSE and mean bias between model and observations are also listed.



Supplementary Figure 3: **Upward migration of the firn line.** Vertical profile of integrated SMB and components including **total precipitation (snowfall and rainfall)**, rainfall, melt, runoff and re-freezing for the periods (a) 1958-1984, (b) 1985-2018, and (c) the difference between the two periods (1985-2018 minus 1958-1984). (d) Hypsometry of Svalbard ice caps, i.e. integrated ice-covered area within 100 m elevation bins. The grey band spans the minimum and maximum ELA (SMB = 0) of individual sectors for the periods 1958-1984 and 1985-2018.



Supplementary Figure 4: **Ablation zone expansion and runoff change.** (a) SMB of Svalbard ice caps averaged for the period 1985-2018. The thick and thin black lines outline the ELA (local SMB = 0) for periods 1958-1984 and 1985-2018. (b) Post-1985 change in meltwater runoff (1985-2018 minus 1958-1984). The black line outlines the 1985-2018 ELA.

Supplementary Table 1: **Model evaluation using recent mass change estimates.** Comparison between mass balance (MB = SMB minus D) from the current study and previous **geodetic, GRACE, model and observation-based mass change estimates.** Models include the **Weather Research and Forecasting model (WRF), the Modèle Atmosphérique Régional (MAR), a Positive Degree Day (PDD) and two Energy Balance Models (EBM).** In our study, solid ice discharge (D) is derived from Ref. ¹ before 2012 and combined Refs. ^{1,2} afterwards.

References	Method	Period	Units	Estimate	This study
Moholdt et al. (2010) ³	Geodetic	2003-2008	Gt yr ⁻¹	-4.1 ± 1.4	-7.1 ± 3.4
Zemp et al. (2019) ⁴	Geodetic	2006-2016	Gt yr ⁻¹	-16.0 ± 8.0	-9.7 ± 3.4
Wouters et al. (2008) ⁵	GRACE	2003-2008	Gt yr ⁻¹	-8.8 ± 3.0	-7.1 ± 3.4
Mèmin et al. (2011) ⁶	GRACE	2003-2009	Gt yr ⁻¹	-9.1 ± 1.0	-6.0 ± 3.4
Gardner et al. (2013) ⁷	GRACE	2003-2009	Gt yr ⁻¹	-6.8 ± 2.0	-6.0 ± 3.4
Jacob et al. (2012) ⁸	GRACE	2003-2010	Gt yr ⁻¹	-3.0 ± 2.0	-5.7 ± 3.4
Matsuo et al. (2013) ⁹	GRACE	2004-2008	Gt yr ⁻¹	-6.8 ± 3.7	-3.6 ± 3.4
Matsuo et al. (2013) ⁹	GRACE	2004-2012	Gt yr ⁻¹	-3.7 ± 3.0	-4.7 ± 3.4
Wouters et al. (2019) ¹⁰	GRACE	2002-2016	Gt yr ⁻¹	-7.2 ± 1.4	-9.3 ± 3.4
Aas et al. (2016) ¹¹	WRF	2003-2013	Gt yr ⁻¹	-8.7	-9.1 ± 3.4
Lang et al. (2015) ¹²	MAR	1979-2013	Gt yr ⁻¹	-8.4	-8.0 ± 3.4
Möller et al. (2018) ¹³	PDD	1957-2010	Gt yr ⁻¹	1.0	-4.1 ± 3.4
Østby et al. (2017) ¹⁴	EBM	1957-2014	Gt yr ⁻¹	-4.0	-5.0 ± 3.4
Van Pelt et al. (2019) ¹⁵	EBM	1957-2018	Gt yr ⁻¹	-3.0	-5.9 ± 3.4
Schuler et al. (2020) ¹⁶	Data upscaling	2000-2019	Gt yr ⁻¹	-8.0 ± 6	-11.4 ± 3.4

Supplementary Table 2: **State of Svalbard glaciers pre-1985**. This table lists the mass balance (MB = SMB minus D), SMB and components, firm refreezing capacity, ablation zone area (i.e. as a fraction of the total glacier area), and ELA (SMB = 0) for individual sectors and the whole of Svalbard averaged over the period 1958-1984. Solid ice discharge (D) is estimated from Ref. ¹. **ELA uncertainty is estimated as one standard deviation of the period 1958-1984**.

1958-1984	Units	NW	NE	VF	AF	BE	SS	Svalbard
MB	Gt yr ⁻¹	-	-	-	-	-	-	-0.4 ± 3.4
SMB	Gt yr ⁻¹	0.3 ± 0.3	2.0 ± 0.4	0.5 ± 0.1	2.9 ± 0.3	0.2 ± 0.1	0.6 ± 0.3	6.3 ± 1.6
Precipitation	Gt yr ⁻¹	4.2	5.5	1.4	5.1	1.6	4.8	23.0
Runoff	Gt yr ⁻¹	3.9	3.5	0.9	2.1	1.5	4.2	16.3
Melt	Gt yr ⁻¹	7.4	6.8	1.5	4.3	1.9	6.4	28.7
Refreezing	Gt yr ⁻¹	4.5	4.1	0.8	2.7	0.7	3.4	16.5
Refreezing capacity	%	57.6	58.7	52.1	60.3	37.2	48.9	54.4
Ablation zone area	%	35.4	25.1	21.5	11.6	36.0	34.8	27.1
ELA	<i>m</i>	470 ± 65	380 ± 100	270 ± 84	220 ± 60	280 ± 80	340 ± 50	350 ± 60

Supplementary Table 3: **State of Svalbard glaciers post-1985**. This table lists the mass balance (MB = SMB minus D), SMB and components, firm refreezing capacity, ablation zone area (i.e. as a fraction of the total glacier area), and ELA (SMB = 0) for individual sectors and the whole of Svalbard averaged over the period 1985-2018. Solid ice discharge (D) is estimated from Ref. ¹ before 2012 and combined Refs. ^{1,2} afterwards. **ELA uncertainty is estimated as one standard deviation of the period 1985-2018**.

1985-2018	Units	NW	NE	VF	AF	BE	SS	Svalbard
MB	Gt yr ⁻¹	-	-	-	-	-	-	-10.2 ± 3.4
SMB	Gt yr ⁻¹	-1.6 ± 0.3	-0.2 ± 0.4	0.0 ± 0.1	1.4 ± 0.3	-0.6 ± 0.1	-1.3 ± 0.3	-2.6 ± 1.6
Precipitation	Gt yr ⁻¹	4.2	5.6	1.3	5.0	1.5	4.7	22.8
Runoff	Gt yr ⁻¹	5.9	5.8	1.3	3.6	2.2	6.0	25.2
Melt	Gt yr ⁻¹	8.9	8.6	1.8	5.5	2.5	7.6	35.4
Refreezing	Gt yr ⁻¹	4.2	3.9	0.7	2.5	0.6	3.0	15.1
Refreezing capacity	%	45.0	43.3	39.2	44.8	23.9	36.1	40.6
Ablation zone area	%	49.0	43.3	41.0	27.5	61.0	51.5	43.9
ELA	<i>m</i>	550 ± 65	510 ± 130	360 ± 100	340 ± 110	370 ± 85	420 ± 55	440 ± 80

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