

Reply to Reviewers

Ken Mankoff *et al.*

Comments from reviewers are in normal font and differentiated from **the replies that use a bold colored font** .

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1 Reviewer 1

1.1 General comments

Review of Mankoff et al. (2021)

This study describes a new operational mass balance product of the Greenland Ice Sheet produced using the input-output method. The different external products used in this study, and the methods for the derivation of this new mass balance estimate are sound and well described. This new mass balance estimate is also compared against independent estimates of mass balance, showing overall good agreement.

I have a few general comments that should not be hard to address:

- In Section 4, I recommend adding a table to summarise the different data products used to generate the final mass balance estimate with the different periods they cover and what field(s) they provide

Added.

- I think that the consistency of the description of the three RCMs in Section 4.3. can be improved by matching the level of details between the different SMB models/products described (for instance what ice mask is used in each RCM)

We've attempted to homogenize the RCM sections.

- I'm not convinced about the difference in MB* between the various IO estimates (Mouginot/This Study and Colgan/This Study) being attributed to differences in SMB as described in the text in sections 6.1 and 6.2. From the figures and the SMB/MMB comparisons, it seems that the differences between the various IO estimates arise from differences in MMB rather than SMB.

We have re-phrased this and clarified that the difference is due to MMB, but it is not apparent because the interannual variability is dominated by SMB.

Overall, this is a great effort to generate the first operational product of Greenland mass balance by making use of already existing methods and data products, which I think will be of interest to anyone interested in the state of the Greenland Ice Sheet. Therefore, I'm happy to recommend this paper to be published after minor revisions.

We're happy you like the concept and the implementation.

I made some specific comments and suggestions below, which I hope will help improve this paper.

We respond to all of your comments below.

1.2 Specific comments

L1: 'Greenland Ice Sheet (GIS) '

We removed all abbreviations for GIS and GrIS.

L5-6: please rephrase this sentence to distinguish the products (from which mass loss is estimated) and the processes (from which the mass loss originates)

We have rephrased the sentence.

L10: 'general agreement with ~~among~~ six other products'

We choose to keep among.

1. Mixed or mingled; surrounded by.
2. Conjoined, or associated with, or making part of the number of; in the number or class of.
3. Expressing a relation of dispersion, distribution, etc.; also, a relation of reciprocal action.

Also because I read a grammar book that states "between" is for 2 options and "among" is for 3 or more. If the proof editors prefer 'with' or 'between' I'll change it then.

L19: 'processes es '

process → processes

L18-21: add typical spatial resolution of the GMB and VC estimates and the typical temporal resolution of VC estimates to quantify what is lower/higher

Done.

L25-26: can you be a bit more specific here: state how frequent ice velocity updates are and the reason for this new capability (for instance new satellite missions (e.g. Sentinel) allowing better temporal sampling of ice velocity time-series)

Done.

L25: I would also add that IO is limited by the scarcity of thickness data in some areas

Done.

L31-32: be more specific here and state the positive and negative SMB fields

Clarified that we use SMB as an input, and do not access the individual components. We list the positive and negative components anyway.

L35: define 'marine mass balance' here

Done.

L35: I'm not sure 'forecasted' is the right word here, as rather than being forecasted the MMB is updated assuming steady-state conditions since the last velocity update

You are correct we did not 'forecast'. However, we've improved the methods here and now 'forecasted' and 'projected' are appropriate.

L61: what 'properties'?

Re-written.

L61-62: 'These This Greenland sum data'

Done

L67: Not sure what you mean by 'includes the restricted [sic] data to 1840' maybe rephrase with something along the lines 'The ice-sheet-wide product includes data

from 1840 through next week while the sector and region-scale products includes data from 1986 through next week.'

Rephrased.

L70: 'are external to this work'.

Added.

L75: By curiosity, why do you use runoff from MAR only? I assume that runoff is also modelled by HIRHAM and RACMO and that the same approach used for the SMB models (i.e. combining the models when they overlap and using MAR runoff from yesterday through next week) could be applied for runoff?

We opted to use only MAR runoff because MAR data included runoff in the initial delivery, while RACMO and HIRHAM included only the SMB field to save transfer bandwidth and storage space. While using all three may be more robust and in-line with the rest of the work, this term is small and the result would not change by including an ensemble BMB_{VHD} term. Using only one RCM saves development and compute time and effort.

L97: specify the min/max of the layer thicknesses

Specified.

L106-107: can you add a few words to specify the benefits of including these observations? Does the model perform better?

Citation added.

L113: specify the min/max thickness of the firm layers in MAR

Done.

L110-123: It's fine to refer the reader to Fettweis et al. (2020) but it would be good to expand this paragraph a bit more, and ensure that the same level of details is provided in each RCM description

We have expanded the MAR section so it contains a similar level of detail as the HIRHAM and RACMO sections.

L114: add citation for the NCEP-NCARv1 reanalysis

Re-written.

L116: 'GridMARv3.10', is it different from MARv3.10?

Rewritten.

L116: no need to mention the inclusion of a new module if it is not used here

Removed.

L121: please provide more background on the recent SMB decrease and the validation with GRACE. This is important as both the SMB and runoff fields are used in this study

Citation added.

L122: 'increase of in runoff'

Changed.

L129-130: is runoff also forecasted? Also add that you use SMB, forecasted SMB and runoff

Runoff was not but is now forecasted. Text revised.

L165: replace 'add [...] a later end date' by 'extend the reconstruction in time up to the end of 2012'

Changed.

L182-183: 'is now updat ing ed'

Changed.

L186: which surface elevation change product do you use?

Citation added.

L211-212: what proportion of the Greenland Ice Sheet bed area is frozen, uncertain or thawed? Can you add the % bed area covered in the text?

Done.

L212: ', (respectively) '

Removed parentheses

L215: on at the ice-sheet scales

Changed 'on' to 'at'

L226: 'these products are the ~~most similar~~ and recent'

Removed.

L261: BMB BMB_{VHD}

Removed.

L272: missing word 'We compute h and [?] from that streams and outlets'

The "that" refers to the h . h is the only input needed for flow routing. We now explicitly state, "We compute h and from h streams and outlets".

L307-308: can you say how much smaller are the Zwally sectors and Mouginot regions compared to the RCM ice domains and what proportion of the SMB losses is not considered if the RCM domain is cropped to the Zwally/Mouginot delineations?

Text updated both to quantify the missing area in Mouginot and Zwally, and the missing SMB from that area. Text also updated to quantify the VHD losses from BedMachine vs. MAR alignment.

Table 1: For IMBIE2, BMB is included in both GMB and VC

Added "or VC"

Table 1: The numbers in the table and in the related figures are slightly different, especially for the bias values (for instance for Mouginot the bias is -4 Gt/yr based on Table 1 and -2 Gt/yr based on Figure 5).

Fixed.

L339: Isn't the MB* difference between This Study and Mouginot dominated by the MMB term rather than the SMB term, with the SMB disagreement adding only a small amount of noise? (You showed before a 23 Gt yr⁻¹ bias in MMB and a very good agreement in terms of SMB between This study and Mouginot)

You are correct. Clarified.

L363-365: Here as well, it seems that the difference in MB* between This Study and Colgan is dominated by differences in MMB, rather than differences in SMB? Or do you speak in terms of short-term temporal variability when you're referring to 'the variation in Colgan et al (2019) MB*'? Either way, this needs to be clarified.

Correct & clarified.

L368: 'peripheral glaciers and ice caps '

Clarified inclusion of peripheral ice masses.

L379: ice sheet boundar ies

Changed.

L391-393: Could the disagreement between This Study and the VC estimates in 1992 and 2019 come from the fact that these two years are the end members of the time-series (perhaps edge effects could be the origin of the disagreement), rather than being driven by changes in the radar scattering horizon? 2012 was also an extreme melt year with the scattering horizon of the radar being shifted upwards closer to the ice sheet surface; however there is a good agreement between This Study and the VC estimates in this particular year (Figure 7b).

It could be edge-effects, although many other years (1995, 1998, 1996) are of similar disagreement. We have added a comment on possible edge effects.

L409: 'assess +es+ '

Removed 'es'

L449: 'and these grid cells are ignored. ~~It is ignored.~~ '

Changed.

Figure 5 and Figure B1: on Figure 5 there is a very good agreement in SMB between This Study and Mouginot (r^2 0.97 and bias -1) but Figure B1 suggests otherwise. It seems from Figure B1 that the agreement in SMB is much lower across all the regions of the Greenland Ice Sheet with $r^2 < 0.40$ for all regions?

Thank you for catching that. The Mouginot data has dates centered in the year, and we correctly aligned dates for the GIS-summed graphic in the main section, but had not done this correctly in the Appendix. The agreement between This

Study and Mougnot (2019) is now also apparent at the region-level shown in the Appendix.

Figures B1 and C1: Is the BMB term included in the MMB and MB* terms here? Specify this in the caption.

By definition BMB is not included because MB* is used. We now add "(excluding BMB)" to the figure captions to make this explicit.

Figures B1 and C1: Maybe use a different yrange for the y-axis for the different regions/sectors as it is difficult to read the figures in some cases (for instance NO, NE or SW MMB)

We made earlier versions with each sector or region y-axis scaled, but opted for this display instead. Yes it makes it difficult to read individual year data for some cases as you pointed out, but highlights inter-sector or inter-region differences (for example, the NO, NE, and SW MMB you highlighted clearly contribute minimal MMB, while SE contributes the most). We prefer to keep the current display which highlights different properties of the data.

2 Review 2 (Andrew Shepherd)

This paper describes an updated mass budget (input output method) for the Greenland Ice Sheet spanning the period 1840 to the present day. From 1986 onwards, the mass budget components are derived from 3 regional climate models, satellite-based estimates of ice discharge, and estimates of basal melting. Prior to 1986, all components are derived from a reconstruction of the surface mass balance and runoff. It is a valuable dataset and deserves to be published.

2.1 Main concerns

I have the following 6 main concerns.

This study introduces a new term – marine mass balance, which is the sum of solid ice discharge and submarine ice melting. I am not convinced that the two terms should be added in this way as one is a lateral flux of ice and the other is a vertical flux of water, and they are in any case representative of different process. It seems to me that they should be kept separate.

In Greenland, unlike Antarctica, submarine melt is usually lateral, not vertical, assuming Greenland marine terminating glaciers have vertical ice fronts, while Antarctic ice shelves float with mostly horizontal surfaces in the water. We disagree that 'melting' is a flux of water - or at least only water. 'Melting' also requires ice. Regardless of the medium both are mass volume flow rate units, not flux units.

I'm not aware that it is possible to separate these terms. Their different values are not known at most glaciers and at most times. There have been a few studies that have examined the ratio of calving to melting (e.g Enderlin et al. (2013) and De Andrés et al. (2018)), or estimate melting from runoff (e.g. Slater et al. (2019) and De Andrés et al. (2021)) but they are poorly constrained and not operational products.

The term is new, but not the data. We point out in the text (L177 of reviewed document) that this is the 'discharge' data (and term) already used in other papers (e.g. Mankoff et al. (2020), King et al. (2020), King et al. (2018), and Enderlin et al. (2014)). We use 'marine mass balance' rather than 'discharge' because a) it matches the other terms (surface mass balance and basal mass balance) and b) we think it is important to highlight that what may be 'solid ice discharge' across the flux gate, splits into calving or melting when it enters a fjord. This distinction is critical for studies of the down-fjord freshwater budget, because submarine melting introduces freshwater at the terminus, and calving introduces freshwater elsewhere, where the icebergs melt.

The submarine melting term is required because the flux gate is positioned in places over floating ice. I question why this is done, given that it adds complexity and uncertainty to the result, and it also means that the result is no longer pertaining to the grounded ice sheet. My recollection is that this term was erroneously included in one mass budget assessment for the Antarctic ice sheet and has since been removed (Rignot et al., 2011). Why not position the flux gate so that no submarine melting is required? I would also like to see more discussion on this submarine melting term and some presentation of the data to illustrate its magnitude and spatial distribution.

The flux gates are not over floating ice. The flux gates are ~5 km upstream from all grounding lines (L179 of reviewed document). We do not know the location and magnitude of submarine melt. This is an area of active research. As soon as this data becomes available we plan to incorporate it into the continually updating product from Mankoff et al. (2020) that is used as an input to This Study.

We could then separate MMB_{calving} from MMB_{melting} , but even then MMB_{calving} should be split into big bergs and small slumping events that effectively melt immediately. Also, in order to be consistent we should then also separate SMB gain (snowfall, rainfall, condensation) from SMB loss (melt, evaporation, sublimation), etc. All this suggests a major update, perhaps as Edition #2 of this paper and product.

It is acknowledged that there are inconsistencies in the domains of the various input datasets at the ice sheet margin, and that this is a location where large signals are present. Some effort is made to align the dataset, but I could not follow the explanation in full. In any case, I would like to see some exploration of the sensitivity of the results to the location of the boundary to be sure that it is not erroneously positioned. This is somehow related to the need to include a submarine melting term; at the location between grounded and floating ice there are typically very large variations in surface and basal ice melting and I am not convinced they can be reliably separated. It would be interesting to see how the various mass balance terms vary as a function of domain size while for example eroding the domain by a pixel at a time.

This is not related to the submarine melt term. That occurs downstream of the MMB flux gates.

If we introduced domain errors by cropping or aligning things we agree that a sensitivity study should be performed. However, we do not introduce domain errors. Your statement that "some effort is made to align the dataset" does not capture the amount of effort we put into correct alignment. We specifically work on the native RCM domains (including rotated pole for the HIRHAM/HARMONIE domain) to make sure that all RCM inputs and outputs are included in this work. We refer readers to Kjeldsen et al. (2020) for an exploration domain issues.

We now include a graphic in the Appendix showing the RCM domain, the Zwally et al. (2012) and Mouginot et al. (2019) (un-expanded), and the expanded Zwally et al. (2012) and Mouginot et al. (2019) that entirely cover the RCM domains with zero losses. We have added paragraphs quantifying the various overlaps.

The one case where we cannot align things correctly is MAR runoff used to estimate BMB_{VHD} . That term is one of three that make up $\sim 24 \text{ Gt yr}^{-1}$ additional mass loss. Because it has a strong seasonal cycle one could argue that the error is 0 Gt yr^{-1} of the BMB term during the winter when there is no runoff, and more during the summer when there is significant runoff. We now quantify the mask area misalignment and 'lost' runoff for that term.

Prior to 1986, the ice sheet mass balance is derived from a scaled reconstruction of surface mass balance and an empirical model of the ice discharge. The SMB is scaled to fit the observations derived from regional climate models post 1986. The ice discharge is modelled as a linear function of the reconstructed runoff based on

a fit to data recorded between 2000 and 2012. This interval is widely recognized to be a highly anomalous period in the Greenland Ice Sheet's history (see e.g. Boers & Rypdale, 2021), and I question the validity of extrapolating a relationship between runoff and discharge obtained from this period to other times. While I recognize that the method was introduced by other authors in 2013, this was prior to the anomaly was established and I believe the validity of the approach needs to be revisited and reestablished. What evidence is there that runoff and discharge were correlated prior to 2000? What happens if a different period is chosen?

The method for scaling discharge from runoff was introduced by Rignot et al. (2008) who scaled SMB anomaly with discharge. Box et al. (2013) isolated runoff as the discharge predictor after a sensitivity analysis. See Box et al. (2013) Figs. 1,2,3,4 and related text, including physical basis. Importantly to the concerns stated above, 1) Box et al. (2013) used 1958, 1964, and 1992-2009 data. Clearly, Fig. 4 in Box et al. (2013) show that 1958 and 1964 and other pre-acceleration years (1992-2004) lie near the regression lines. Furthermore, while 2000 through 2006 cover a changing period in Greenland discharge, there were likely other 'anomalous' periods in the past. There is independent evidence that the 1920s or 1940s may have been periods of significant discharge increase.

We have added some of this information to the manuscript.

I have some concerns related to uncertainties as I could not find answers in the text. When the reconstructed SMB is scaled to the regional climate model data, is the dispersion added as an additional uncertainty to the scaled reconstruction? Similarly, when the ice discharge is modelled from the reconstructed runoff, is the dispersion added as an additional uncertainty?

We now include the following text in the manuscript:

For reconstructed SMB and MMB, the mean of the recent uncertainty is added to the reconstructed uncertainty during the adjustment. Reconstructed MB uncertainty is then re-calculated as the square root of the sum of the squares of the reconstructed SMB and MMB uncertainty.

We implement that in the code, and the reconstructed time series uncertainty is visibly larger in Figure 2.

Finally, it is assumed that the basal and surface mass balance uncertainties do not have time-invariant components, but I find this difficult to believe. What evidence is there for this?

In the direct comparison between SMB observations and modelling, there is evidence that the errors are randomly distributed in time. Based on the limited data available which resolve SMB in time over longer periods, this seems to hold if you look at local comparison of ablation along the K-transect since 1990 (Fig. 9 in Noël et al. (2018)). Finally, comparison with time series from satellite products (similar epoch) does not show a clear deterioration/improvement in time (Fig. 7 in this paper). There is little information available before the 1990s to check for earlier epochs. In Overly et al. (2016), GPR derived accumulation support a stable uncertainty going back to 1980s.

We have revised our uncertainty treatment and now assume MMB and BMB_{GF} are time invariant (bias), but SMB, BMB_{VHD}, and BMB_{friction} are time-varying (random).

Note however that these assumptions are only relevant for Fig. 4 where we accumulate errors in time. We do not use or provide this information for the output of this work - that is, the published data. There is only one error term there, and it includes both systematic and random error. We are not aware of other products that publish two error terms distinguishing between random and bias, but are eager to improve our methods if the editor or reviewers can provide a relevant citation with example.

We have added text to the "Accumulating uncertainties" section that clarifies this.

I would like to see each of the terms produced in this paper plotted and tabulated, i.e. SMB components (at least runoff and snowfall), ice discharge, submarine melting, basal melting.

The current work uses a single SMB term from the model outputs. At no point (in this work) do we separate SMB inputs and outputs. We clarify this in the text. Ice discharge and submarine melting are not (and I argue cannot at the moment) be separated. We have generated a Figure 2 with MMB and BMB separated, but do not believe it provides useful information, because BMB is so small relative to the other terms.

We are not sure how to present this in tabular form. There are too many days. Annual or decade? Average or sum? The data is accessible in an easy-to-access format (CSV) and NetCDF, and we provide code to display it.

2.2 Minor concerns

I have the following minor concerns:

L3: be clear about the period of data v models

Done.

L5: not sure you need to contrast performance to other mass balance estimates

Removed.

L6: and in any case which elements update daily?

Clarified. After 1986, all elements update daily (1 SMB term, all three BMB terms) except MMB, which updates every 12 days.

L9: define "general agreement"

Added range of r^2 values.

L10: say a little more about which other products are referred to here

Added.

L14: im not sure this statement is correct as there have been a large number of studies reporting trends in the ice sheet mass loss. We do know where, when, how, and why

the ice sheet has changed in mass. I think it would be a good idea to include a short summary here since it is absent elsewhere in the introduction.

We have re-written the 2nd sentence of the Introduction.

L21: im not sure "no information" is correct. Locating the imbalance in space is informative

Locating in space is certainly informative, but that is 'where' not 'how'. GRACE does not provide "information on the process contributing to changes in mass balance components (how)" (L19/20).

L22: I don't think defintion is the correct word here, perhaps drop "definition of"

Dropped.

L24: integrated, not reduced

We choose to keep 'reduced'.

L24: suggest "typically" rather than "still"

Changed.

L26: i think you need to be careful about the sampling afforded by the satellites as compared to datasets made publicly available

We are not sure exactly what you are referring to. VC products are usually higher spatial resolution than GMB products. We use the word 'satellite' throughout the document, but never with respect to spatial resolution. Here we are referring to public products.

L26: this is not true; all methods give some information on processes its just integrated in the case of the raw VC and GMB methods but even in this case is informative because of the localisation. But in any case the methods are now routinely complemented also with RCM data to partition into dynamics and SMB as is done with IO. So I think the wording should be tightened up here. The IOM data are of clear value and its not necessary to diminish the value of other methods

We agree, but that 'integration' you refer to is precisely what removes the 'how'. Localisation is 'where', not 'how'. We are not sure what the 'complement' is, but believe RCM data is external to VC and GMB products, which is what we are discussing here. We have slightly re-written this paragraph to note that a) we do not have separate SMB terms as mentioned above and b) removed "is the only one".

L32: Suggest "Inputs" not "IO inputs"

Re-written, but we believe it is important to distinguish between "IO inputs" and "Inputs to this study", the latter which may include IO outputs (i.e., we use data from Mouginot et al. (2019)).

L33: Suggest "Outputs" not "IO outputs"

See above.

L34: is it really annual for each component? I think you are oversampling the discharge for example and undersampling the RCM data

Clarified that we are oversampling discharge. We are not undersampling RCM data - it is provided at daily resolution for the recent, and annual for the historical. RCMs may have O(minutes) timestep internally. We do not describe that here.

L36: probably worth explaining to the reader what you mean here (presumably that the data will continue to be updated independent of this paper)

Added 'daily-updating'.

L37: suggest move the "Terminology" section to a glossary

We prefer to keep it here.

L38: "Product description" seems more like text for the acknowledgements or a footnote of some kind. In any case it should presumably come after the methods and results are reported

We choose to keep it here - Because this is a 'data description' paper we believe it is appropriate to describe the output data near the beginning of the document. We will gladly re-arrange at the suggestion of the editor.

L252: its only future relative to this dataset, its present relative to all the others

Word 'future' removed.

L280: suggest "start" instead of "top"

Changed.

L294: suggest add e.g. "relative to recent data" after "slope" to clarify

Clarified.

L307: do you mean data products not aligned, or their domains? Also, aligned in space (not time)

We meant 'ice masks' and have changed the wording.

L311: are you extrapolating data or interpolating it? I can't really tell. And are you resampling to a common grid?

There is no interpolation. We are not sure how one would interpolate between 'CW' and 'NW' or sector 8.1 and 8.2 (without creating new sector 8.15). Therefore, extrapolation. The Zwally and Mouginot vector data is rasterized onto the native grid of HIRHAM, MAR, and RACMO.

L350: what does large uncertainty mean?

Removed 'large'.

L413: not true, imbie data are equally weighting across all techniques present

Adjusted text.

3 References

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Greenland ice sheet mass balance from 1840 through next week

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Abstract. The mass of the Greenland ice sheet is declining as mass gain from ~~snowfall~~ snow accumulation is exceeded by mass loss from surface meltwater runoff, marine-terminating glacier calving and submarine melting, and basal melting. Here we use the input/output (IO) method to estimate mass change from 1840 through next week. ~~Mass gains come from~~ Surface mass balance (SMB) gains and losses come from a semi-empirical SMB model from 1840 through 1985, and three regional climate models (RCMs; HIRHAM/HARMONIE, MAR, and RACMO) ~~and a semi-empirical surface mass balance (SMB) model. Mass from 1986 through next week. Additional non-SMB~~ losses come from the RCMs, a statistical SMB model, ice discharge at marine terminating glaciers, and ice melted at the base of the ice sheet ~~a marine terminating glacier ice discharge product and a basal mass balance model~~. From these products we provide an annual estimate of GIS Greenland ice sheet mass balance from 1840 through 1985 and a daily estimate at sector and region scale from 1986 through next week. ~~Compared with other mass balance estimates, this~~ This product updates daily ~~, has higher temporal resolution,~~ and is the first IO product to include the basal mass balance which is a source of an additional ~~~8 %~~ 24 Gt yr⁻¹ of mass loss. Our results demonstrate an accelerating GIS-scale ice-sheet-scale mass loss and general agreement (coefficient of determination, r^2 , ranges from 0.62 to 0.94) among six other products, including gravitational, volume, and other IO mass balance estimates. Results from this study are available at <https://doi.org/10.22008/FK2/OHI23Z> (Mankoff et al., 2021).

1 Introduction

Over the past several decades, mass loss from the Greenland ice sheet has increased ~~. However, exactly where, when, and how that mass has been lost is not precisely known.~~ (Khan et al., 2015; The IMBIE Team, 2019). Different processes dominate the regional mass loss of the ice sheet, and their relative contribution has fluctuated in time (Mouginot and Rignot, 2019). For example, in the 1970s nearly all sectors gained mass due to positive SMB, except the northwest sector where discharge losses

20 ~~dominated. More recently in the 2010s, all sectors lost mass, with some sectors losing mass almost entirely via negative SMB, and others primarily due to discharge (Fig. 1).~~

There are three common methods for estimating mass balance – changes in gravity (Barletta et al., 2013; Groh et al., 2019; The IMBIE Team, 2019; Velicogna et al., 2020), changes in volume (Simonsen et al., 2021a; Sørensen et al., 2011; Zwally and Giovinetto, 2011; Sasgen et al., 2012; Smith et al., 2020), ~~or and~~ the input/output (IO) method (Colgan et al., 2019; Mouginot et al., 2019; Rignot et al., 2019; King et al., 2020). Each provides some estimate of where, when, and how the mass is lost or gained, and each method has some limitations. The gravity mass balance (GMB) estimate has ~~very-low-low ~100 km~~ spatial resolution (where), monthly temporal resolution (when), and ~~no-little~~ information on the ~~process-processes~~ contributing to changes in mass balance components (how). The volume change (VC) mass balance estimate has ~~higher-spatial-resolution-than GMB ~1 km spatial resolution~~ (where), ~~lower-temporal-resolution-than GMB often provided on annual or multi-year temporal resolution~~ (when), and ~~again-no-with little~~ information on the ~~process-driving processes~~ (how).

The IO method has a complex ~~definition-of~~ spatial resolution (where). The inputs ~~typically~~ come from regional climate models (RCMs) ~~and therefore have km-scale spatial resolution much higher than GMB and on the order of VC which can reach a spatial resolution of up to 1 km.~~ However, that spatial resolution is generally reduced in the final output to sector or region scale – ~~still-typically~~ higher than GMB but now lower resolution than VC. The IO temporal resolution (when) is limited by ice velocity data updates, which for the past several years occur ~~more-frequently-than GMB and VC updates. Finally, every 12 days year-round after the launch of the Sentinel missions~~ (Solgaard et al., 2021). ~~The primary issue with the IO method is the only one that unknown ice thickness in some locations (e.g. Mankoff et al. (2020b)). Finally, the IO method can provide insight into the processes (how) by distinguishing between changes in-mass-gain (e.g., snowfall); and changes in-caused by SMB (which may be due to changes in positive and/or negative SMB components) vs. changes in other mass loss terms (e.g., surface melting vs.-calving).~~ Our IO method is also the first IO product to include the basal mass balance (Karlsson et al., 2021) – a term implicitly included in the GMB and VC methods but neglected by all previous IO estimates.

In this work we introduce the new PROMICE Greenland ice sheet mass balance dataset based on the IO method, updating the previous product from Colgan et al. (2019). ~~IO inputs are the positive SMB fields from one RCM (We use the SMB field from one empirical model from 1840 through 1985) to three RCMs (, and three RCMs from 1986 onward), IO outputs are the negative SMB fields from the same RCM(s),.~~ The combined SMB field used here is comprised of positive SMB terms (precipitation in the form of snowfall, rainfall, and condensation/riming) and negative SMB terms (surface melt, evaporation, sublimation, and snow drift erosion/deposition). We also use the basal mass balance, and an estimate of dynamic ice discharge. Spatial resolution is effectively per sector (Zwally et al., 2012) or region (Mouginot and Rignot, 2019). Temporal resolution is annual from 1840 through 1985, and ~~daily since 1986. The effectively daily since 1986 - the~~ RCM fields are updated daily and ~~forecasted through next week, and~~ the marine mass balance (i.e., discharge at marine terminating glaciers) is updated every 12 days ~~and forecasted with ~12 day resolution, interpolated to daily, and forecasted using historical and seasonal trends through next week.~~ Thus, this study provides ~~an-a daily-updating~~ estimate of Greenland mass changes from 1840 through next week.

2 Terminology

We use the following terminology throughout the document:

- 55 – ~~'This Study'~~ This Study refers to the new results presented in this study.
- ~~'Recent'~~ Recent refers to the new 1986 through next week daily temporal resolution data at region and sector scale
- ~~'Reconstructed'~~ Reconstructed refers to the adjusted Kjeldsen et al. (2015) annual temporal resolution data at ~~GIS-scale~~ data-ice sheet scale used to extend this product from 1986 back through 1840. The 1986 through 2012 portion of the Kjeldsen et al. (2015) data set is used only to adjust the reconstructed data, then discarded.
- 60 – ROI (region of interest) refers to one or more of the ice sheet sectors or regions (Fig. 1).
- Sector refers to one of the Zwally et al. (2012) sectors (Fig. 1), expanded here to cover the RCM ice domains which exist slightly outside these sectors in some locations.
- Region refers to the Mouginot and Rignot (2019) regions (Fig. 1), expanded here to cover the RCM ice domains.
- SMB is the surface mass balance from an RCM.
- 65 – MMB is the marine mass balance, which in other works is often referred to as solid ice discharge or D. It includes both calving and submarine melting.
- BMB is the basal mass balance. It comes from geothermal flux (BMB_{GF}), frictional heating from ice velocity ($BMB_{friction}$), and viscous heat dissipation (BMB_{VHD}).
- MB is the total mass balance including the BMB term (Eq. 3).
- 70 – MB* is the mass balance not including the BMB term (Eq. 4).
- HIRHAM/HARMONIE, MAR, and RACMO refer to the RCMs, which only provide SMB, and runoff in the case of MAR. However, when referencing the different MB products, we use, for example, "MAR MB" rather than repeatedly explicitly stating "MB derived from MAR SMB minus BMB and MMB". The use should be clear from context.

3 Product ~~Description~~description

- 75 The output of this work is two NetCDF files and one CSV file containing a time series of mass balance and the components used to calculate mass balance. The only difference between the two NetCDF files is the ROI – one for Zwally et al. (2012) sectors and one for Mouginot and Rignot (2019) regions. Each ~~also includes properties summed across the entire ice sheet. This Greenland sum data are also the contents of the CSV file. Each~~ NetCDF file includes the ice sheet mass balance (MB), MB per region of interest (ROI; sector or region), MB per ROI per RCM, ice sheet surface mass balance (SMB), SMB per ROI,

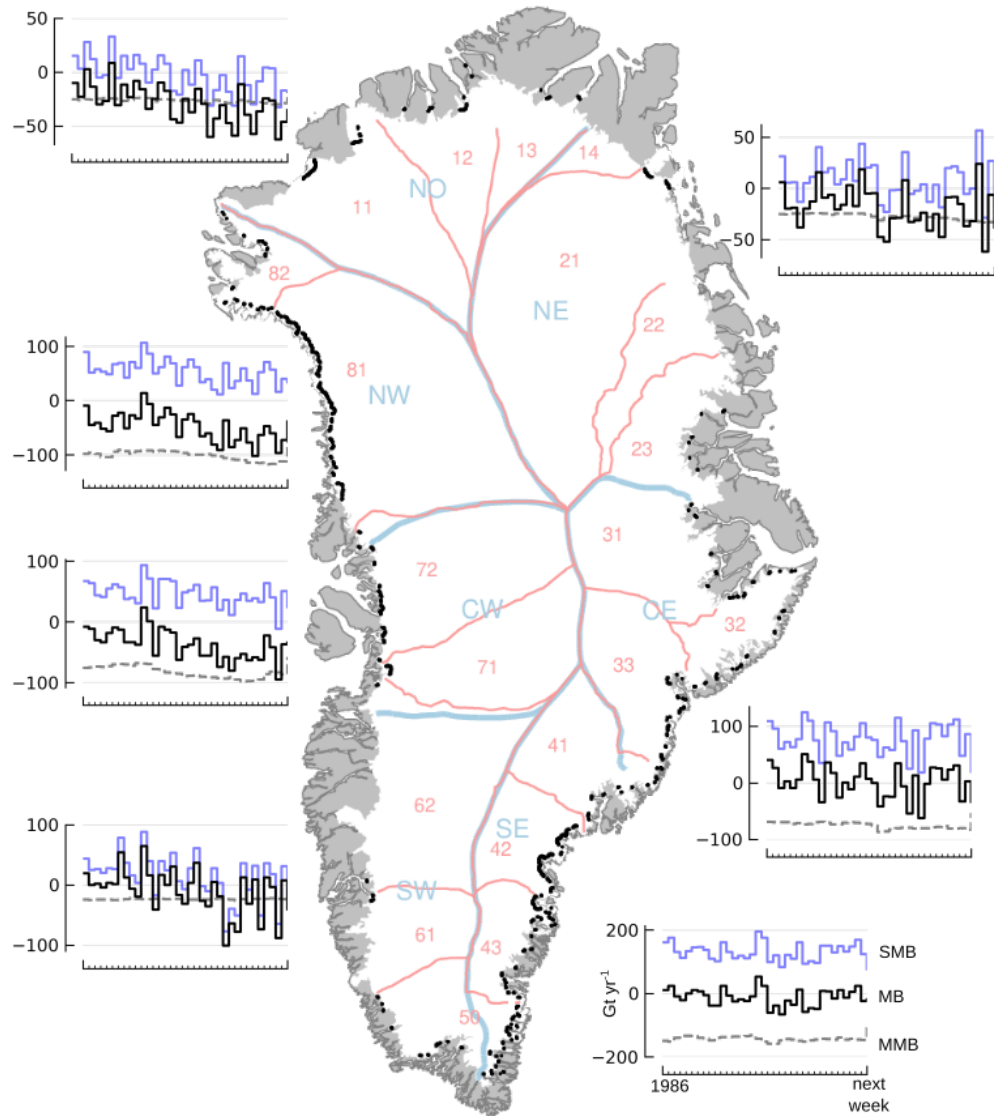


Figure 1. Annual mass balance (black lines), surface mass balance (blue lines) and marine plus basal mass balance (dashed grey) in Gt yr^{-1} for each of the seven Mouginot and Rignot (2019) regions. The map shows both the named regions (Mouginot and Rignot, 2019) and the numbered sectors (Zwally et al., 2012). Marine mass balance gates are the marked in black blobs near glacier termini. Only recent (post-1986) data are shown because reconstructed data are not separated into regions or sectors. Next week is defined as 2021-05-01 to 2021-08-20 based on the date this document was compiled.

80 ice sheet marine mass balance (MMB), MMB per ROI, ice sheet basal mass balance (BMB), and BMB per ROI. [The CSV file contains a copy of the ice-sheet summed data.](#)

An example of the output is shown in Fig. 2, where the top panel shows mass balance for the entire Greenland ice sheet, in addition to SMB, and MMB, at annual resolution. The lower panel shows an example two years at daily temporal resolution.

~~Because this is~~ The ice-sheet-wide ~~the product includes the reconstructed data to 1840. At sector or region scale, only recent~~
 85 ~~data are provided~~ product includes data from 1840 through next week, but the sector and region-scale products only includes
data from 1986 through next week, because the 1840 through 1985 reconstructed only exists at ice-sheet scale (Fig. 1).

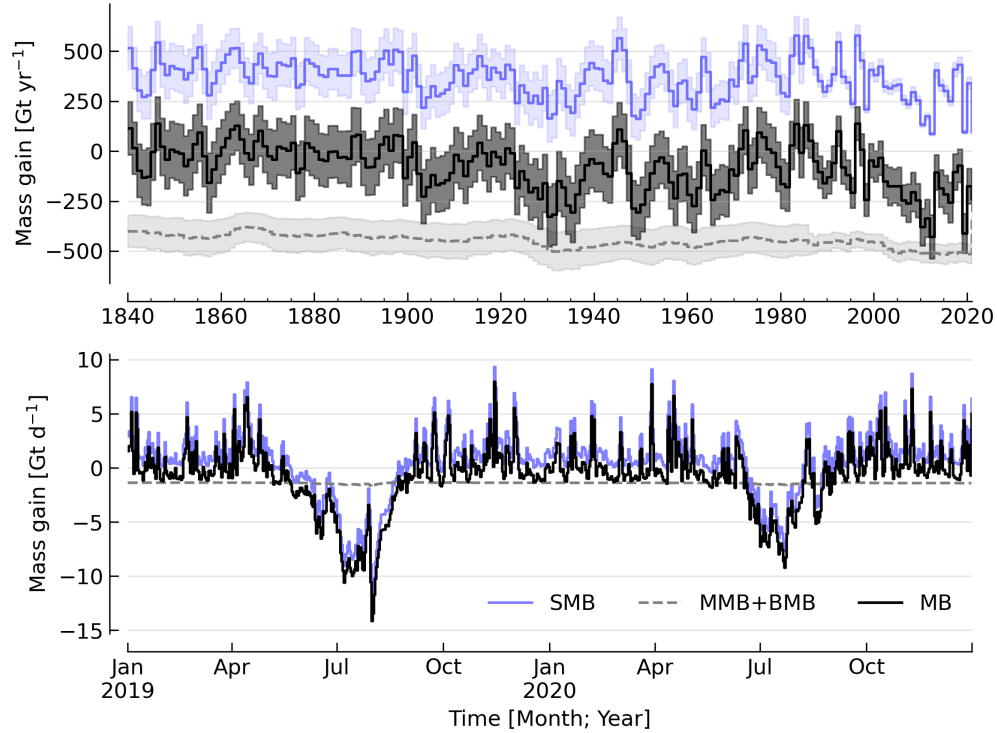


Figure 2. Mass balance and its major components. Top panel: Annual average surface mass balance (blue line), marine mass balance (gray dashed), and their mass balance sum (black line). Here the marine and basal mass balance (MMB + BMB) are shown with sign inverted (e.g. $-1 \times (\text{MMB} + \text{BMB})$) Lower panel: Same data at daily resolution and limited to 2019 and 2020.

4 Data ~~Sources~~sources

This section introduces data products that exist prior to and are external to this work (Table 1). In the following Methods section we introduce both the intermediate products we generate using these data sources, and the final product that is the output of

90 This Study.

The inputs to this work are the recent SMB fields from the three RCMs, the recent marine mass balance data from Mankoff et al. (2020b) (data: Mankoff and Solgaard (2020)), and the recent basal mass balance fields, of which BMB_{GF} and $BMB_{friction}$ are direct outputs from Karlsson et al. (2021) (data: Karlsson (2021)), but the BMB_{VHD} calculations are redone here (see Methods Sect. 5.3) using the MAR runoff field. The reconstructed data (pre 1986) are surface and marine mass balance from 95 Kjeldsen et al. (2015) (data: Box et al. (2021)), but adjusted here using the overlapping period (see Methods Sect. 5.4), and runoff from Kjeldsen et al. (2015) (data: Box et al. (2021)) as a proxy and scaled for BMB_{VHD} (see Methods Sect. 5.3).

Table 1. [Summary of data products used as inputs to This Study.](#)

Product	Period	Reference	Data / Notes
Reconstructed SMB	1840 through 1985	Kjeldsen et al. (2015)	Box et al. (2021)
Reconstructed MMB	1840 through 1985	Kjeldsen et al. (2015)	Box et al. (2021)
HIRHAM/HARMONIE SMB	1986 through yesterday	Langen et al. (2017)	
MAR SMB	1986 through next week	Fettweis et al. (2020)	
RACMO SMB	1986 through last month	Noël et al. (2019)	
MMB	1986 through last month	Mankoff et al. (2020b)	Mankoff and Solgaard (2020)
BMB_{GF}; BMB_{friction}	1840 through next week	Karlsson et al. (2021)	Karlsson (2021)
BMB_{VHD}	1840 through 1985	Kjeldsen et al. (2015)	Box et al. (2021) reconstructed runoff
BMB_{VHD}	1986 through next week	Fettweis et al. (2020)	MAR runoff

4.1 Surface mass balance

We use one reconstructed SMB from 1840 through 1985, and three recent SMB from 1986 through last month (HIRHAM/HARMONIE, MAR, and RACMO), two through yesterday (HIRHAM/HARMONIE and MAR) and one through next week (MAR).

100 4.1.1 HIRHAM/HARMONIE

The HIRHAM/HARMONIE product from the Danmarks Meteorologiske Institut (Danish Meteorological Institute; DMI) is based on an offline subsurface firn/SMB model (Langen et al., 2017), which is forced with surface fluxes of energy (turbulent and downward radiative) and mass (snow, rain, evaporation, and sublimation). These surface fluxes are derived from the HIRHAM5 regional climate model for the reconstructed part of the simulation and from DMI's operational numerical weather 105 forecast model HARMONIE (Iceland-Greenland domain "B", which covers Iceland, Greenland, and the adjacent seas) for the real-time part. HIRHAM5 is used until 2017-08-31 after which HARMONIE is used.

The HIRHAM5 regional climate model (Christensen et al., 2007) combines the dynamical core of the HIRLAM7 numerical weather forecasting model (Eerola, 2006) with physics schemes from the ECHAM5 general circulation model (Roeckner et al., 2003). In the Greenland setup employed here (Lucas-Picher et al., 2012), it has a horizontal resolution of $0.05^\circ \times 0.05^\circ$ on a 110 rotated pole grid (corresponding to 5.5 km resolution), and 31 atmospheric levels in the vertical. It is forced at 6 hr intervals on the lateral boundaries with horizontal wind vectors, temperature, and specific humidity from the ERA-Interim reanalysis

(Dee et al., 2011). ERA-Interim sea surface temperatures and sea ice concentration are prescribed in ocean grid points. Surface fluxes from HIRHAM5 are passed to the offline subsurface model.

The offline subsurface model was developed to improve firn details for the HIRHAM5 experiments (Langen et al., 2017).

115 The subsurface consists of 32 layers with time-varying fractions of snow, ice and liquid water. Layer thicknesses increase with depth ~~and give from 6.5 cm water equivalent (w.e.) at the top to 9.2 m w.e. at the bottom giving~~ a full model depth of 60 m ~~water equivalent w.e.~~ The processes governing the firn evolution include snow densification, varying hydraulic conductivity, irreducible water saturation and other effects on snow liquid water percolation, and retention. Runoff is calculated from liquid water in excess of the irreducible saturation with a characteristic local timescale that depends on surface slope (Zuo and
120 Oerlemans, 1996; Lefebvre, 2003). The offline subsurface model is run on the HIRHAM5 5.5 km grid.

For the real-time data we use DMI's operational numerical weather forecast model HARMONIE (Bengtsson et al., 2017), a nonhydrostatic model in terrain-following sigma coordinates based on the fully compressible Euler equations (Simmons and Burridge, 1981; Laprise, 1992). HARMONIE is run at 2.5 km horizontal resolution and with 65 vertical levels. Compared to previous model versions, upper air 3D variational data assimilation of satellite wind and radiance data, radio occultation data,
125 radiosonde, aircraft, and surface observations are incorporated. This ~~is important, as there are only few~~ greatly improves the number of observations in the model, as in situ observations ~~in Greenland from ground stations and radiosondes only make up approximately 20 % of observations in Greenland~~ (Wang and Randriamampianina, 2021; Yang et al., 2018). The model is driven at the boundaries with European Centre for Medium-Range Weather Forecasts (ECMWF) high-resolution data at 9 km resolution. The 2.5 km HARMONIE output is regridded to the 5.5 km HIRHAM grid before input to the offline subsurface
130 model. The HIRHAM5 and the offline model both employ the Citterio and Ahlström (2013) ice mask interpolated to the 5.5 km grid.

4.1.2 MAR

The Modèle Atmosphérique Régional (MAR) RCM has been developed by the University of Liège (Belgium) with a focus on the polar regions (Fettweis et al., 2020). The MAR atmosphere ~~model module~~ (Gallée and Schayes, 1994) is fully coupled with
135 ~~a snow energy balance model the soil-ice-snow energy balance vegetation model SISVAT~~ (Gallée et al., 2001) simulating the evolution of the ~~25–30~~ first meters of snow/ice. ~~See Fettweis et al. (2020) for a full description and validation of MAR over Greenland over the ice sheet with the help of 30 snow layers (with time varying thickness) or the 10 first meter of soil over the tundra area.~~ At its lateral boundary, MAR is 6 hourly forced by the reanalysis ~~NCEP-NCARv1 and run ERA5 and runs~~ at a resolution of 20 km ~~using the same setup as presented by Tedesco and Fettweis (2020), but using~~. The snow pack has been
140 initialised in 1950 from a former MARv3.11 .5 for This Study, while Fettweis et al. (2020) and Tedesco and Fettweis (2020) used based simulation. Its snow model is based on a former version of the CROCUS snow model (Vionnet et al., 2012) dealing with all the snowpack processes including the meltwater retention, transformation of melting snow and grain size, compaction of snow, formation of ice lenses impacting meltwater penetration, warming of the snowpack from rainfall, and complex snow/bare ice albedo. MAR uses the Greenland Ice Mapping Project (GIMP) ice sheet mask and ice sheet topography
145 (Howat et al., 2014).

The new version, MAR 3.12, is used here. With respect to version 3.9 intensively validated over Greenland (Fettweis et al., 2020) or the 20 km based MARv3.9 and GridMARv3.10, respectively. The main improvements of set-up used in Tedesco and Fettweis (2020). MARv3.12 now uses the common polar stereographic projection EPSG 3413. With respect to MARv3.11 are the inclusion of a blowing snow module (however, not used over Greenland) in addition to fully described in Amory et al. (2021). MARv3.12 assures now the full conservation of water mass into both soil and snowpack at each time step, takes into account of the geographical projection deformations in its advection scheme, better deals with the snow/rain temperature limit with a continuous temperature threshold between 0 and -2°C, increases the evaporation above snow thanks to a saturated humidity computation in SISVAT adapted to freezing temperatures, disallows melt below the 30 m of the resolved snowpack, includes small improvements and bug corrections-fixes with the aim of improving the evaluation of MAR (with both in situ and satellite product/products) as presented in Fettweis et al. (2020) in addition to small computer time improvements in the parallelisation of its code.

In addition to providing SMB, MAR also provides daily runoff –over both permanent ice and tundra area – this is used for the daily BMB_{VHD} estimate (Section 5.3).

As the recent SMB decrease (successfully evaluated with GRACE based estimates in Fettweis et al. (2020)) has been fully driven by the increase of runoff, we can in runoff (Sasgen et al., 2020), we assume the same degree of accuracy between SMB simulated by MAR (evaluated with the PROMICE SMB database (Fettweis et al., 2020)) and the runoff simulated by MAR.

Weather-forecasted SMB: To provide a real-time state of the Greenland ice sheet, MAR is forced automatically everyday by the run of 00h-00h UTC from the Global Forecast System (GFS) model providing weather forecasting initialised by the snowpack behaviors-behaviours of the MAR run from the previous day. This continuous GFS forced time series (without any reinitialisation of MAR) provides SMB and runoff estimates between the period covered by NCEP-NCAR-ERA5 and the next 7 days. At the end of each day, NCEP-NCARv1-ERA5 is used to update the GFS forced MAR time series until about 5 days before the current date and to provide an homogeneous NCEP-NCARv1-ERA5 forced MAR times series from 1948-1950 to a few days before the current date. We use both the forecasted SMB and runoff-fields-forecasted runoff (for BMB_{VHD}) fields.

4.1.3 RACMO

The Regional Atmospheric Climate MOdel (RACMO) v2.3p2 has been developed at the Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute; KNMI). It incorporates the dynamical core of the High-Resolution Limited Area Model (HIRLAM) and the physics parameterizations of the ECMWF Integrated Forecast System cycle CY33r1. A polar version (p) of RACMO has been developed at the Institute for Marine and Atmospheric research of Utrecht University (UU-IMAU), to assess the surface mass balance of glaciated surfaces. The current version RACMO2.3p2 has been described in detail in Noël et al. (2018), and here we repeat the main characteristics.

The ice sheet has an extensive dry interior snow zone, a relatively narrow runoff zone along the low-lying margins, and a percolation zone of varying width in between. To capture these processes in first order, the original single-layer snow model in RACMO has been replaced by a 40-layer snow scheme that includes expressions for dry snow densification and a simple tipping bucket scheme to simulate meltwater percolation, retention, refreezing, and runoff (Ettema et al., 2010). The snow layers are

180 initialized in September 1957 using temperature and density from a previous run with the offline IMAU Firn Densification Model (Ligtenberg et al., 2018). To simulate drifting snow transport and sublimation, Lenaerts et al. (2012) implemented a drifting snow scheme. Snow albedo depends on snow grain size, cloud optical thickness, solar zenith angle, and impurity content (van Angelen et al., 2012). Bare ice albedo is assumed constant and estimated as the fifth percentile value of albedo time series (2000-2015) from the 500 m resolution MODIS 16-day albedo product (MCD43A3). Minimum/maximum values
185 of 0.30/0.55 are applied to the bare ice albedo, representing ice with high/low impurity content (cryoconite, algae).

To simulate as accurately as possible the contemporary climate and surface mass balance of the ice sheet, the following boundary conditions have been applied. The glacier ice mask and surface topography have been down-sampled from the 90 m resolution Greenland Ice Mapping Project (GIMP) digital elevation model (~~DEM; Howat et al. (2014)~~)(Howat et al., 2014). At the lateral boundaries, model temperature, specific humidity, pressure, and horizontal wind components at the 40 vertical
190 model levels are relaxed towards 6-hourly ECMWF reanalysis (ERA) data. For this we use ERA-40 between 1958 and 1978 (Uppala et al., 2005), ERA-Interim between 1979 and 1989 (Dee et al., 2011), and ERA-5 between 1990 and 2020 (Hersbach et al., 2020). The relaxation zone is 24 grid cells (~130 km) wide to ensure a smooth transition to the domain interior. This run has active upper atmosphere relaxation (van de Berg and Medley, 2016). Over glaciated grid points, surface aerodynamic roughness is assumed constant for snow (1 mm) and ice (5 mm). In this run, RACMO2.3p2 has 5.5 km horizontal resolution
195 over Greenland and the adjacent oceans and land masses, but it was found previously that this is insufficient to resolve the many narrow outlet glaciers. The 5.5 km product is therefore statistically downscaled onto a 1 km grid sampled from the GIMP DEM (Noël et al., 2019), employing corrections for biases in elevation and bare ice albedo using a MODIS albedo product at 1 km resolution (Noël et al., 2016).

4.1.4 Reconstructed

200 The Kjeldsen et al. (2015) 173-year (1840 through 2012) mass balance reconstruction is based on the Box (2013) 171-year (1840 through 2010) statistical reconstruction. Kjeldsen et al. (2015) add a more sophisticated meltwater retention scheme (Pfeffer et al., 1991); weighting of in situ records in their contribution to the estimated value; dispersal of annual accumulation to monthly; and ~~a later end date, i.e.,~~ extend the reconstruction in time through 2012.

The Box (2013) 171-year (1840-2010) reconstruction is developed from linear regression parameters that describe the least
205 squares regression between a-) spatially discontinuous in situ monthly air temperature records (Cappelen et al., 2011; Cappelen, 2001; Cappelen et al., 2006; Vinther et al., 2006)) or firn/ice cores (Box et al., 2013) and b-) spatially continuous outputs from regional climate model RACMO version 2.1 (Ettema et al., 2010). A 43-year overlap period (1960 through 2012) with the RACMO data are used to determine regression parameters (slope, intercept) on a 5 km grid cell basis. Temperature data define melting degree days, which have a different coefficient for bare ice than snow cover, determined from hydrological-
210 year cumulative SMB. A fundamental assumption is that the calibration factors, regression slope, and offset for the calibration period 1960 through 2012 are stationary over time for which there is some evidence of in Fettweis et al. (2017). Box et al. (2013) describes the methods in more detail.

The reconstructed surface mass balance is adjusted as described in the Methods Sect. 5.4 (Fig. 3).

4.2 Marine mass balance

The recent marine mass balance data are the discharge (D) product from Mankoff et al. (2020b) (data: Mankoff and Solgaard (2020)). This product covers all fast-flowing ($> 100 \text{ m yr}^{-1}$) marine-terminating glaciers. The marine mass balance in Mankoff et al. (2020b) is computed at flux gates $\sim 5 \text{ km}$ upstream from glacier termini (Mankoff, 2020), using a wide range of velocity products, and ice thickness from BedMachine v3 (~~supplemented in the SE Greenland with ice thickness from Millan et al. (2018)~~)v4. Discharge across flux gates is derived with a 200 m spatial resolution grid, but then summed and provided at glacier resolution. Temporal coverage begins in 1986 with a few velocity estimates, and is ~~now updating~~ updated each time a new velocity product is released, which is every ~ 12 days with a ~ 30 day lag (Solgaard et al., 2021) (data: Solgaard and Kusk (2021)).

Some changes have been implemented since the last publication describing the marine mass balance product ~~in detail~~ (i.e., Mankoff et al. (2020b)). These are minor and include updating the Khan et al. (2016) (data: Khan (2017)) surface elevation change product from 2015 through 2019, updating various MEaSUREs velocity products to their latest version, ~~and~~ updating the PROMICE Sentinel ice velocity product from Edition 1 (doi:10.22008/promice/data/sentinel1icevelocity/greenlandicesheet/v1.0.0) to Edition 2 (Solgaard et al. (2021); Solgaard and Kusk (2021)), ~~and updating from BedMachine v3 (supplemented in the SE with Millan et al. (2018)) to use only BedMachine v4~~ (Morlighem et al., 2021).

The reconstructed marine mass balance data (Kjeldsen et al., 2015) are estimated via a linear fit between unsmoothed annual marine mass balance spanning 2000 to 2012 (Enderlin et al., 2014) and runoff data from ~~Kjeldsen et al. (2015)~~ (Kjeldsen et al., 2015) using a 6-year trailing average. The ~~physical basis for the marine mass balance parameterization using runoff is described in Box and Colgan (2013) method for scaling discharge from runoff was introduced by~~ (Rignot et al., 2008), ~~who scaled the SMB anomaly with discharge. Sensitivity analyses conducted by Box and Colgan (2013) showed runoff to be the more effective discharge predictor, and include a discussion of the physical basis. Although the fitting period of the present dataset includes an anomalous period of discharge (2000 through 2005; e.g., Boers and Rypdal (2021)), the discharge data used by Rignot et al. (2008) and Box and Colgan (2013) also includes years 1958 and 1964 that lie near the regression line (See Box and Colgan (2013) Fig. 4 and related section 4. Physical basis). Further, while 2000 through 2005 cover a changing period in Greenlandic discharge (Mankoff et al., 2020b; King et al., 2020), there were likely other anomalous periods in the past, when glaciers in Greenland experienced considerable increases in discharge as inferred by geological and geodetic investigations~~ (Andresen et al., 2012; Björk et al., 2012; Khan et al., 2015, 2020).

The reconstructed marine mass balance is adjusted as described in the Methods Sect. 5.4.

4.3 Basal mass balance

The basal mass balance (BMB; Karlsson et al. (2021)) comes from mass lost at the bed from geothermal flux (BMB_{GF}), frictional heating ($\text{BMB}_{\text{friction}}$) from the basal shear velocity, and viscous heat dissipation (BMB_{VHD}) from surface runoff routed to the bed (i.e. the volume of the subglacial conduits formed from surface runoff; Mankoff and Tulaczyk (2017)).

These fields (data: Karlsson (2021)) are provided as steady state annual estimates. We use the BMB_{GF} and $BMB_{friction}$ products and apply 1/365th to each day, each year. Because BMB_{VHD} is proportional to runoff, an annual estimate is not appropriate for this work with daily resolution. We therefore re-calculate the BMB_{VHD} -induced basal melt as described in Methods Sect. 5.3.

250 4.3.1 Geothermal Flux

Due to a lack of direct observations, the geothermal flux is poorly constrained under most of the Greenland ice sheet. Different approaches have been employed to infer the value of the BMB_{GF} often with diverging results (see e.g., Rogozhina et al. (2012); Rezvanbehbahani et al. (2019)). Lacking substantial validation that favours one BMB_{GF} map over the others, Karlsson et al. (2021) instead use the average of three widely used BMB_{GF} estimates: Fox Maule et al. (2009); Shapiro and Ritzwoller (2004),
255 and Martos et al. (2018). The BMB_{GF} melt rate is calculated as

$$\dot{b}_m = E_{GF} \rho_i^{-1} L^{-1}, \quad (1)$$

where E_{GF} is available energy at the bed, here the geothermal flux in units $W m^{-2}$, ρ_i is the density of ice ($917 kg m^{-3}$), and L is the latent heat of fusion ($335 kJ kg^{-1}$; Cuffey and Paterson (2010)). BMB_{GF} melting is only calculated where the bed is not frozen. We use ~~MacGregor et al. (2016)~~ the MacGregor et al. (2016) estimate of temperate bed extent and scale Eq. 1 by 0,
260 0.5, or 1 where the bed is frozen ~~-, uncertain (~25 % of the ice sheet area), uncertain (~33 %), or thawed (respectively) ~42 %),~~
respectively.

4.3.2 Friction

This heat term stems from the friction produced as ice slides over the bedrock. The term has only been measured in a handful of places (e.g., Ryser et al. (2014); Maier et al. (2019)) and it is unclear how representative those measurements are ~~on~~ at ice-sheet
265 scales. Karlsson et al. (2021) therefore estimate the frictional heating using the Full Stokes Elmer/Ice model that resolves all stresses while relating basal sliding and shear stress using a linear friction law (Gillet-Chaulet et al., 2012; Maier et al., 2021). The model is tuned to match a multi-decadal surface velocity map (Joughin et al., 2018) covering 1995-2015 and it returns an estimated basal friction heat that is used to calculate the basal melt due to friction, similar to Eq. 1:

$$\dot{b}_m = E_f \rho_i^{-1} L^{-1}, \quad (2)$$

270 where E_f is energy due to friction. We also apply the 0, 0.5, and 1 scale as used for the BMB_{GF} term (MacGregor et al., 2016) in order to mask out areas that are likely frozen.

4.4 Other

ROI regions come from Mouginot and Rignot (2019) and ROI sectors come from Zwally et al. (2012).

4.5 Products used for validation

275 We validate This Study against five other data products ([See Table 2 and Sect. 6](#)). These products are the most ~~similar and~~
recent IO product (Mouginot et al., 2019), the previous PROMICE mass balance product (Colgan et al. (2019); data: Colgan
(2021)), the two mostly-independent methods of estimating ice sheet mass change: GMB (Barletta et al. (2013); data: Barletta
et al. (2020)) and VC (Simonsen et al. (2021a); data: Simonsen et al. (2021b)), and the IMBIE2 data (The IMBIE Team, 2019).
In addition to this we evaluate the reconstructed Kjeldsen et al. (2015) (data: Box et al. (2021)) and This Study data during the
280 overlapping period 1986 through 2012. ~~Results of the validation are in Sect. 6.~~

5 Methods

The total mass balance for all of Greenland and all the different ROIs involves summing each field (SMB, MMB, BMB) by
each ROI, then subtracting the MMB and BMB from the SMB fields, or,

$$MB = SMB - MMB - BMB. \quad (3)$$

285 Products that do not include the BMB term (i.e., Mouginot et al. (2019); Colgan et al. (2019), and Kjeldsen et al. (2015))
have total mass balance defined as

$$MB^* = SMB - MMB, \quad (4)$$

~~And and~~ when comparing This Study to those products, we compare like terms, never comparing our MB to a different
product MB^{*}, except [in](#) Fig. 4 where all ~~data products are graphed~~ [products are shown](#) together.

290 Prior to calculating the mass balance, we perform the following steps.

5.1 Surface mass balance

In This Study we generate an output based on each of the three RCMs (HIRHAM/HARMONIE, MAR, and RACMO), however,
in addition to these we generate a final and 4th SMB field defined as a combination of 1) the adjusted reconstructed SMB from
1840 through 1985 (Sect. 5.4), and 2) the average of HIRHAM/HARMONIE, MAR, and RACMO from 1986 through a few
295 months ago when RACMO drops ~~out~~ [are available](#), the average of HIRHAM/HARMONIE and MAR from a few months ago
through yesterday, and MAR from yesterday through next week. See the Appendix A for differences among This Study MB
and MB derived using each of the RCM SMBs. There is no obvious change or step function at the 1985 to 1986 reconstructed-
to-recent change, nor as the RACMO and then HIRHAM/HARMONIE RCMs ~~drop out of the time series,~~ [become unavailable](#)
a few months ago and yesterday, respectively.

300 5.2 ~~Forecasted-Projected~~ marine mass balance

We ~~estimate future project the~~ marine mass balance ~~as steady from the most recent estimate from the last observed point from~~ Mankoff et al. (2020b) (generally between 2 weeks and 1 month old) ~~-Ice discharge changes annually to seven days into the~~ future at each glacier. We define the long-term trend as the linear least squares fit to the last three years of observed data. We define the seasonal signal as the mean of the last three years of observed data during the temporal window of interest that spans
 305 ~~from the most recently available observation through to present plus one week. We then assign the long term trend plus the~~ seasonal signal value to next week's MMB (i.e., now + 7 days), and finally linearly interpolate between the last observed value and the forecasted next week's value, to provide the recent past projected and future forecasted MMB.

Marine mass balance does not change sign and changes magnitude by approximately 6 % ~~annually~~ over the entire ice sheet (King et al., 2018), ~~suggesting a maximum of one-month change of less than 6 %~~ but surface mass balance changes sign and
 310 has much larger and short-term variability. From this, the statistical forecast for marine mass balance described above does not impact results as much as the physically-based model forecast for surface mass balance.

5.3 Basal mass balance

Because Karlsson et al. (2021) provide a steady-state annual-average estimate of the BMB fields, we divide the BMB_{GF} and ~~friction-velocity (BMB_{friction})~~ BMB_{friction} fields by 365 to estimate daily average. This is a reasonable treatment of the BMB_{GF}
 315 field, which does not have an annual cycle. The BMB_{friction} field does have a small annual cycle that matches the annual velocity cycle. However, when averaged over all of Greenland, this is only a ~6 % variation (King et al., 2018), and Karlsson et al. (2021) found that basal melt rates are 5 % higher for summer maps. Thus, the intra-annual changes are less than the uncertainty. The BMB~~BMB~~_{VHD} field varies significantly throughout the year, because it is proportional to surface runoff. We therefore generate our own BMB_{VHD} for this study.

320 To estimate recent BMB_{VHD} we use daily MAR runoff (see Mankoff et al. (2020a)) and BedMachine ~~v3-v4~~ (Morlighem et al., 2017, 2021) to derive subglacial routing pathways, similar to Mankoff and Tulaczyk (2017). We assume that all runoff travels to the bed within the grid cell where it is generated, the bed is pressurized by the load of the overhead ice, and the runoff discharges on the day it is generated. We calculate subglacial routing from the gradient of the subglacial pressure head surface, h , defined as

$$325 \quad h = z_b + k \frac{\rho_i}{\rho_w} (z_s - z_b), \quad (5)$$

with z_b the basal topography, k the flotation fraction (1), ρ_i the density of ice (917 kg m⁻³), ρ_w the density of water (1000 kg m⁻³), and z_s the ice surface. Eq. 5 comes from Shreve (1972), where the hydropotential has units of pascals (Pa), but here it is divided by gravitational acceleration g times the density of water ρ_w to convert the units from pascals to meters (Pa to m).

We compute h and from ~~that~~ h streams and outlets, and both the pressure and elevation difference between the source
 330 and outlet. The energy available for basal melting is the elevation difference (gravitational potential energy) and two-thirds

of the pressure difference, with the remaining one third consumed to warm the water to match the changing phase transition temperature (Liestøl, 1956; Mankoff and Tulaczyk, 2017). We assume all energy, E_{VHD} (in Joules), is used to melt ice with

$$b_m = E_{\text{VHD}} \rho_i^{-1} L^{-1}. \quad (6)$$

Because results are presented per ROI and to reduce the computational load of this daily estimate, we only calculate the
 335 integrated energy released between the RCM runoff source cell and the outlet cell, and then assign that to the ROI containing the runoff source cell.

To estimate reconstructed basal mass balance, we treat BMB_{GF} and $\text{BMB}_{\text{friction}}$ as steady state as described at the ~~top~~ start of this section. For BMB_{VHD} we use the fact that VHD comes from runoff by definition, and from this, reconstructed BMB_{VHD} is calculated using scaled runoff as a proxy. VHD theory suggests that a unit volume of runoff that experiences a 1000 m
 340 elevation drop will release enough heat to melt an additional 3 % (Liestøl, 1956). To estimate the scale factor we use the 1986 through 2012 overlap between Kjeldsen et al. (2015) runoff and This Study recent BMB_{VHD} from MAR runoff described above. The correlation between the two has an r^2 value of ~~0.78~~0.75, slope of ~~0.043~~0.03, and an intercept of ~~-5~~-3 Gt yr^{-1} (Appendix D). From this, we scale the Kjeldsen et al. (2015) reconstructed runoff by ~~4.3 %~~3 % (from the 0.03 slope, unrelated to the theoretical 1000 m drop described earlier) to estimate reconstructed BMB_{VHD} .

345 5.4 Reconstructed adjustment

We use the reconstructed and recent surface (SMB) and marine (MMB) mass balance overlap from 1986 through 2012 to adjust the reconstructed data. This Study vs reconstructed SMB has a slope of 0.6 and an intercept of 165 Gt yr^{-1} (Fig. 3 SMB), and This Study vs reconstructed MMB has a slope of 1.1 and an intercept of -6 Gt yr^{-1} (Fig. 3 MMB). The unadjusted reconstructed data slightly underestimates years with high SMB and overestimates years with low SMB (see 1986, 2010, 2011, and 2012 in
 350 Fig. 3 SMB). The unadjusted reconstructed data slightly overestimates years with low MMB and overestimates years with high MMB.

We adjust the reconstructed data until the reconstructed vs. recent slope is 1 and ~~the~~ intercept is 0 Gt yr^{-1} for each of the surface and marine mass balance comparisons (Fig. 3). We then derive the BMB_{VHD} term for reconstructed basal mass balance (Sect. 5.3 and Appendix D), bring in the other BMB terms (Sect. 5.3), and use Eq. 3 to ~~find the~~ compute the adjusted
 355 reconstructed mass balance.

For reconstructed SMB and MMB, the mean of the recent uncertainty is added to the reconstructed uncertainty during the adjustment. Reconstructed MB uncertainty is then re-calculated as the square root of the sum of the squares of the reconstructed SMB and MMB uncertainty.

For surface mass balance, the adjustment is effectively a rotation around the mean values, with years with low SMB decreasing and years with high SMB increasing after the adjustment. For marine mass balance, years with low MMB are slightly
 360 reduced, and years with high MMB have a higher reduction to better match the overlapping estimates.

The adjustment described above treats all biases in the reconstructed data. The primary assumption of our adjustment is that the bias contributions do not change in proportion to each other over time.

~~Given high correlations, we find it reasonable to~~ We attribute the disagreement ~~and need for the adjustment~~ to the demonstrated too-high biases in accumulation and ablation estimates in the 1840-2012 ~~statistical reconstruction SMB reconstructed~~ SMB field (Fettweis et al., 2020), an offset resulting from differences in ice masks (Kjeldsen et al., 2015), the inclusion of peripheral glaciers (Kjeldsen et al., 2015), other accumulation rate inaccuracies (Lewis et al., 2017, 2019), and other unknowns.

5.5 Domains, ~~Boundaries~~boundaries, and regions of interest

Few of the ~~data products ice masks~~ used here are spatially aligned. The Zwally et al. (2012) sectors and the Mouginot and Rignot (2019) regions are often smaller than the RCM ice domains. For example, the RACMO ice domain is 1,718,959 km², of which 1,696,419 km² (99 %) are covered by the Mouginot and Rignot (2019) regions, and 22,540 km² (1 %) are not, or 1,678,864 km² (98 %) are covered by the Zwally et al. (2012) and 40,095 km² (2 %) are not.

Cropping the RCM domain edges would remove the edge cells where the largest SMB losses occur. This effect is minor when SMB is high (years with low runoff, assuming SMB magnitude is dominated by the runoff term). This effect is large when SMB is low (years with high runoff). As an example for the 2010 decade, RACMO SMB has a mean of 251 Gt yr⁻¹ for the decade, with a low of 45 Gt in 2019, a high of 420 Gt in 2018. For these same extreme years RACMO cropped to Mouginot and Rignot (2019) has a low of 76 Gt (68 % high) and a high of 429 Gt (2 % high). RACMO cropped to Zwally et al. (2012) has a low of 84 Gt (85 % high) and a high of 429 Gt (2 % high).

We therefore grow the ROIs to cover the RCM domains. ROIs are grown by expanding them outward, assigning the new cells the value (ROI classification, that is sector number or region name, see Fig. 1) of the nearest non-null cell, and then clipping to the RCM ice domain. This is done for each ROI and RCM. Appendix E provides a graphical display of the HIRHAM RCM domain, the Mouginot and Rignot (2019) domain, and our expanded Mouginot and Rignot (2019) domain.

BMB_{VHD} comes from the MAR ice domain runoff, but is generated on the BedMachine ice thickness grid, which is smaller than the ice domain in some places. Therefore, the largest runoff volumes per unit area (from the low-elevation edge of the ice sheet) are discarded in these locations.

6 Product evaluation and assessment

We compare to six related data sets (see ~~See~~Table 2 and Sect. 4.5): The most similar and recent IO product (Mouginot et al., 2019), the previous PROMICE assessment (Colgan et al., 2019), the two mostly independent methods (GMB (Barletta et al., 2013) and VC (Simonsen et al., 2021a)), IMBIE2 (The IMBIE Team, 2019), and the unadjusted reconstructed/recent overlap (Kjeldsen et al., 2015).

Our initial comparison (Fig. 4) shows all seven products overlaid in a time series accumulating at the product resolution (daily to annual) from the beginning of the first overlap (1972, Mouginot et al. (2019)) until seven days from now (now defined as ~~2021-04-24~~2021-08-13). Each data set is manually aligned vertically so that the last timestamps appear to overlap,

allowing disagreements to grow back in time. We also assume errors are smallest at present and allow errors to grow back in time. The errors for this product are described in the Uncertainty section.

In the sections below, we compare This Study to each of the validation data in more detail. The Mouginot et al. (2019) and Colgan et al. (2019) products allow term-level (SMB, MMB, and MB*) comparison, and the GMB, VC, and IMBIE2 only MB-level comparison. The MB or MB* comparison for each product is summarized in Table ???. All have different masks. Bias [Gt yr⁻¹] is defined as $\frac{1}{n} \sum_{i=1}^n (x_i - y_i)$. RMSE [Gt yr⁻¹] is defined as $\sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - y_i)^2}$. Sums are computed using ice-sheet wide annual values, where x is This Study, y is the other product, and a positive bias means that This Study has a larger value.

Table 2. Summary of correlation, bias, and RMSE between different products during their overlap periods with This Study. Basal mass balance not included in This Study when comparing against Mouginot and Rignot (2019), Colgan et al. (2019), or Kjeldsen et al. (2015). Peripheral ice masses never included in This Study.

Other product	r ²	bias	RMSE	Fig.	Overlap	Notes
Mouginot et al. (2019)	0.96 0.94	-4 9	29 36	5	1986 – 2018	No basal mass balance
Colgan et al. (2019)	0.88 0.87	-50 -35	69 61	6	1995 – 2015	No basal mass balance
GMB	0.87 0.86	13 30	54 62	7	Includes peripherals 2002 – 2020	<u>Includes peripheral masses</u>
VC	0.64 0.62	-29 -14	89 85	7	1992 – 2019	Multi-year smooth
IMBIE2	0.89	-25 -10	50 44	7	1992 – 2018	No BMB when using IO; BMB when using G
Kjeldsen et al. (2015)	0.82 0.80	-5 3	60 59	3	1986 – 2012	No basal mass balance; Includes peripherals pe

6.1 Mouginot (2019)

The Mouginot et al. (2019) product spans the 1972 through 2018 period. The SMB ~~originates from the~~comes from RACMO v2.3p2 downscaled at 1 km, and agrees very well with SMB from This Study (r² ~~0.97~~, bias ~~-1~~, RMSE ~~18~~, slope ~~1.00~~ . 94, bias 9, RMSE 36, slope 1.1). The minor SMB differences are likely due to mask differences, or our use of a three-RCM average SMB estimate, ~~or perhaps updates to the RACMO model since the Mouginot et al. (2019) study.~~

Mouginot et al. (2019) discharge and our MMB from Mankoff et al. (2020b) have a ~~-23~~-33 Gt yr⁻¹ bias. This difference can mainly be attributed to different discharge estimates in the Southeast and Central east sector (Appendix: Mouginot regions). When we include BMB in This Study (diamonds in middle panel shifting values to the right), it adds ~25 Gt yr⁻¹ to This Study. Because MB* is a linear combination of SMB and MMB terms (Eq 4), the MB* ~~difference~~differences between this product and Mouginot et al. (2019) ~~is~~are dominated by the SMB term. ~~The MMB disagreement adds only a small amount of noise to the overall agreement~~MMB term, although it is not apparent because interannual variability is dominated by SMB.

6.2 Colgan (2019)

The Colgan et al. (2019) product spans 1995 through 2015. The SMB term is broadly similar to the RCM-averaged SMB term in This Study, although Colgan et al. (2019) use only an older version of MAR (Fig. 6 top panel). The Colgan et al. (2019)

SMB is spatially interpolated over the PROMICE ice-sheet ice mask (Citterio and Ahlstrøm, 2013), which contains more detail on the ice sheet periphery, ~~but also and therefore~~ a larger ablation area than the native coarser MAR ice mask. This Study does not interpolate the SMB field and instead works on the SMB ice domain and.

The most critical difference between This Study and Colgan et al. (2019) is that the latter estimate grounding line ice discharge based on corrections to ice volume flow rate measured across the approximately 1700 m elevation contour. This ice volume flow rate measurement is far inland relative to the grounding line flux gates used in This Study (from Mankoff (2020)). This introduces ~~large~~-uncertainty in the Colgan et al. (2019) MMB term induced by the SMB corrections between the 1700 m elevation contour and the terminus (see large disagreement in Fig. 6 mid panel). This disagreement increases when BMB is included in the results of This Study (shown by dots shifting the annual values to the right).

The MMB disagreement is represented differently across sectors (Appendix: Colgan 2019), where sectors 1, 2, 5, and 6 all have correlation coefficients less than ~0.1, while the remaining sectors 3, 4, 7, and 8 all have correlation coefficients greater than 0.5.

This Study assesses greater MMB bias (~~54~~ 43 Gt yr⁻¹) than Colgan et al. (2019). While Colgan et al. (2019) did not assess BMB, the majority (~~>85%~~) of this discrepancy likely results from Colgan et al. (2019) aliasing the aforementioned downstream correction terms. For example, while This Study shows very little ~~inter-annual~~ interannual variability in ice discharge in the predominantly land-terminating SW region, Colgan et al. (2019) infer large ~~inter-annual~~ interannual variability in ice discharge based on large ~~inter-annual~~ interannual variability in SMB and changes in ablation area ice volume in their Sector 6. The discrepancy between This Study and Colgan et al. (2019) MMB [+BMB] is largest during the earliest part of the record (i.e. 1995-2000), decreasing towards present-day, which may suggest that Colgan et al. (2019) particularly overestimated the response in ice discharge to 1990s climate variability.

Similar to the comparison with Mouginot et al. (2019), the ~~variation in Colgan et al. (2019) MB* is also ultimately dominated by variation in the SMB term. This leads to strong agreement between this study and the Colgan et al. (2019) estimated annual MB* disagreement between This Study and Colgan et al. (2019) is dominated by MMB disagreement, although it is again not apparent because interannual variability is dominated by SMB.~~

6.3 Gravimetric Mass Balance (GMB)

~~The primary difference between GMB and This Study is that~~ Unlike this Study, the GMB method includes mass losses and gains on peripheral ~~glaciers~~ ice masses which should introduce a bias of ~10 to 15% ~~, while This Study does not include peripheral glaciers~~ (Colgan et al., 2015; Bolch et al., 2013). The inclusion of peripheral ~~glaciers~~ ice in the GMB product is because the spatial resolution is so low that it cannot distinguish between them and the main ice sheet. There is also signal leakage from other glaciated areas, ~~eg. e.g.~~ the Canadian Arctic. This can have ~~a major~~ an effect on the estimated signal, especially in sectors 1 and 8 or regions NW and NO. There is also leakage between basins, which becomes a larger issue for smaller basins or where major outlet glaciers are near basin boundaries. GMB may also have an amplified seasonal signal due to changing snow loading in the surrounding land areas that may be mapped as ice sheet mass change variability. This would enhance the seasonal amplitude but not have an impact on the ~~inter-annual~~ interannual mass change rates. Additionally, different glacial isostatic

adjustment (GIA) corrections applied to the gravimetric signal may also lead to differences in GMB estimates on ice sheet scale, but also on sector scale (e.g. Sutterley et al. (2014); Khan et al. (2016)).

GMB and the IO method (This Study) both report changes in ice sheet mass, but they are measuring two fundamentally different things. The IO method tracks volume flow rate across the ice sheet ~~boundary~~boundaries. Typically this is meltwater across the ice sheet surface and solid ice across flux gates near the calving edge of the ice sheet, and in This Study also meltwater across the ice sheet basal boundary. That volume is then converted to mass. We consider that mass is ‘lost’ as soon as it crosses the boundary (i.e. the ice melts or ice crosses the flux gate). The GMB method tracks the regional mass changes. Melting ice has no impact on this, until the meltwater enters the ocean and a similar mass leaves the far-field GMB footprint. From these differences, the GMB method may be a better estimate of sea level rise, while the ~~IO~~IO method may be a better representation of the state of the Greenland ice sheet.

6.4 Volume ~~change~~Change (VC)

When deriving surface elevation change from satellite altimetry, data from multiple years are needed to give a stable ice sheet-wide prediction. Hence, the altimetric mass balance estimates are often reported as averages of single satellite missions.

Although This Study has a small (~~-29~~-14 Gt yr⁻¹) bias in comparison to Simonsen et al. (2021a) VC, there is a relatively high RMSE of ~~89~~85 Gt yr⁻¹ and a mid-range correlation ($r^2 = \del{0.64}\del{0.62}$). This suggests that while both This Study and VC agree on the total mass loss of the ice sheet, they disagree on the precise temporal distribution of this mass loss. ~~The~~It is possible the outlying 1992 and 2019 years are influenced by the edge of the time series record if not fully sampled, but other outliers exist - the 1992 extreme low melt year and the 2019 extreme melt year, as well as the ~~1996-1998~~1995 through 1998 period, stand out as years ~~of especially~~with poor agreement.

We suggest that this is due to climate influences on the effective radar horizon across the ice sheet during these years. Weather-driven changes in the effective scatter horizon, mapped by Ku-band in the upper snow layer of ice sheets hampers the conversion of radar-derived elevation change into mass change (Nilsson et al., 2015). Simonsen et al. (2021a) used a machine learning approach to derive a temporal calibration field for converting the radar elevation change estimates into mass change. This approach relied on precise mass balance estimates from ICESat to train the model and thereby was able to remove the effects of the changing scattering horizon in the radar data. This VC mass balance is given for monthly time steps (Simonsen et al., 2021a), however the running-mean applied to derive radar elevation change will dampen the interannual variability of the mass balance estimate from VC. This is especially true prior to 2010, after which the novel radar altimeter onboard CryoSat-2 allowed for a shortening of the data windowing from 5 to 3 years. This smoothing of the interannual variability is also seen in the intercomparison between This Study and the VC MB, where in addition to the two end members of the time series (1992 and 2019) the years 1995, 1996, and 1998 seem to be outliers (Fig. 7). These years are notable for high MB which seems to be captured less precisely by the older radar altimeters due to the longer temporal averaging.

6.5 IMBIE

The most widely cited estimate of Greenland mass balance today is the Ice-Sheet Mass Balance Inter-Comparison Exercise 2 (IMBIE2, The IMBIE Team (2019)). IMBIE2 seeks to provide a consensus estimate of monthly Greenland mass balance between 1992 and 2018 that is derived from altimetry, gravimetry, and input-output ensemble members. There are two critical methodological differences between This Study and IMBIE2. Firstly, the gravimetry members of IMBIE2 ~~assesses~~assess mass balance of all ~~Greenland~~Greenlandic land ice, including peripheral ice masses, while This Study only assesses mass balance of the ice sheet proper. Secondly, the input-output members of IMBIE2 do not assess BMB, while This Study does.

~~Of the 26 independent estimates in the~~The IMBIE2 ~~assessment 9 are from satellite altimetry composite record of ice-sheet mass balance equally weights three methods of assessing ice-sheet mass balance: input-output, altimetry and gravimetry.~~ Prior to c. 2003, ~~however,~~ IMBIE2 is derived ~~using only the IO method solely from IO studies that explicitly exclude BMB (MB is actually MB*), while after,~~ After c. 2003, it is mostly driven by the variability of GRACE dampened by the longer averaging in the altimetry. by comparison, IMBIE2 includes both satellite altimetry and gravimetry records implicitly sample BMB. The representation of BMB in the composite IMBIE2 mass balance record therefore shifts before and after c. 2003.

In comparison to mass balance assessed by IMBIE2, This Study has a small bias of $\sim -24 - 10$ Gt yr⁻¹ over the ~~common~~ 26 calendar year comparison period. This apparent agreement may be attributed to the compensating effects of IMBIE2 effectively sampling peripheral ice ~~eaps~~masses and ignoring BMB, while This Study does the opposite and ignores peripheral ice ~~eaps~~masses but samples BMB, equal to ~ 25 Gt yr⁻¹. Over the entire 26-year comparison period, the RMSE with IMBIE2 is $\sim 50 - 44$ Gt yr⁻¹ and the correlation is $0.890 - 0.89$. This relatively high correlation highlights good agreement in interannual variability between studies, and the RMSE suggests that formal stated uncertainties of each study (c. ± 30 to ± 63 Gt yr⁻¹ for IMBIE2 and mean of $88 - 86$ Gt yr⁻¹ for This Study) are indeed good estimates of the true uncertainty, as assessed by inter-study discrepancies.

7 Uncertainty

We treat the three inputs to the total mass balance (surface, marine, and basal mass balance, or SMB, MMB, and BMB) as independent when calculating the total error. This is a simplification – the RCM SMB and the BMB_{VHD} from RCM runoff are related, and MMB ice thickness and BMB_{VHD} pressure gradients are related, and other terms may have dependencies. However, the two dominant IO terms, SMB inputs and MMB outputs, are independent on annual time scales, and for simplification we treat all terms as independent. We use Eq 3 and standard error propagation for SMB, MMB, and BMB terms (i.e., the square root of the sum of the squares of the SMB plus MMB plus BMB error terms). For the MMB, extra work is done to calculate uncertainty between the last Mankoff 2020 MMB data (up to 30 days old, with error of $\sim 10 - 9$ % or $\sim 50 - 45$ Gt yr⁻¹) and the forecasted now-plus-7-day MMB (see Sect. 7.1). Table 3 provides a summary of the uncertainty for each input.

The final This Study MB uncertainty value shown in Table 3 comes from ~~the average value~~mean of the annual sum of the MB error term~~after summing by year and computing the mean of the uncertainty.~~

Term	Uncertainty [\pm]	Notes
HIRHAM / HARMONIE SMB	15 %	Langen et al. (2017). The mean accumulation bias (-5%) and ablation bias (-7%) tend to cancel out, but this cannot be expected to be the case on single-basin, short-term scales where uncertainty is estimated to be larger.
MAR SMB	15 %	Fettweis et al. (2020). The mean bias between the model and the measurements was 15 % with a maximum of 1000 mmWE yr ⁻¹ . GrSMBMIP uses integrated values over several months of SMB, suggesting larger uncertainty of modeled runoff at the daily timescale.
RACMO SMB	15 %	Noël et al. (2019). Average 5% runoff bias compared to annual cumulative discharge from the Watson River. Increases to a maximum of 20 % for extreme runoff years.
This Study SMB	9 %	Average of 15 % SMB uncertainties above, assuming uncorrelated.
Reconstructed SMB	~ 20 %	From Kjeldsen et al. (2015) Table 1.
Recent MMB	~50 ~45 Gt yr ⁻¹	~10 ~9 %. Mankoff et al. (2020b) updated (Mankoff, 2021) .
Reconstructed MMB	~ 10 %	From Kjeldsen et al. (2015) Table 1.
BMB _{GF}	50 %	5.3 +4/-1.4 Gt yr ⁻¹ from Karlsson et al. (2021) Table 1, using the average of the three available methods.
BMB _{friction}	20 %	11.8 \pm 3.4 Gt yr ⁻¹ from Karlsson et al. (2021) Table 1.
BMB _{VHD}	15 %	MAR runoff uncertainty.
This Study MB	~88 ~86 Gt yr ⁻¹	Eq 3, assuming all uncertainty is uncorrelated.

Table 3. Summary of uncertainty estimates for products used in This Study. This is an approximate and simplified representation – RCM uncertainties are calculated separately for gain and loss terms, because SMB near 0 does not mean uncertainty is near 0. This is also why the final This Study uncertainty is presented with units [Gt yr⁻¹].

7.1 Marine mass balance

The MMB uncertainty is ~~adjusted from the forecasted MMB based on reconstructed the MMB variability. For the forecast~~
515 ~~period we estimate the uncertainty based on data from all previous years. On~~ [discussed in detail in Mankoff et al. \(2020b\)](#), but
[the main uncertainties come from unknown ice thickness, the assumption of no vertical shear at fast-flowing marine-terminating](#)
[outlet glaciers, and ice density of 917 kg m⁻³. Regional ice density can be significantly reduced by crevasses. For example,](#)
[Mankoff et al. \(2020c\) identified a snow-covered crevasse field with 20 % crevasse density, meaning at that location regional](#)
[firn density should be reduced by 20 %.](#)

520 Temporally, MMB at daily resolution comes from ~12 day observations up-sampled to daily, and those ~12 day resolution observations come from longer time period observations (Solgaard et al., 2021). Because the velocity method using feature tracking, it is correct on average but misses variability within each sample period (e.g., Greene et al. (2020)).

525 Spatially, MMB discharge is estimated ~5 km upstream from the grounding lines for ice velocities as low as 100 m yr^{-1} . That ice accelerates toward the margin, but even ice flowing steady at 1 km yr^{-1} would take 5 years before that mass is lost. However, at any given point in time, ice that had previously crossed the flux gate is calving or melting into the fjord. The discrepancy here between the flux gate estimated mass loss and the actual mass lost at the downstream terminus is only significant for glaciers that have had large velocity changes at some point in the recent past, large changes in ice thickness, or large changes in the location (retreat or advance) of the terminus. We do not consider SMB changes downstream of the flux gate, because the gates are temporally near the terminus for most of the ice that is fast-flowing, and the largest SMB uncertainty is at the ice sheet margin where there are both mask issues and high topographic variability.

530 The forecasted MMB uncertainty is estimated from the same forecasted calendar days of the last three years of observed MMB at each glacier. MMB uncertainty for the first forecasted day ~~the uncertainty is increased from the baseline approximate 10 % by adding 2 standard deviations of the daily variability in MMB on that calendar date throughout our record. On is the~~ baseline MMB uncertainty plus the largest daily change observed during the forecast period from the last three years. The MMB uncertainty for the second forecasted day ~~we do the same, and then use the larger of that value or the previous days value (i.e., uncertainty cannot decrease as the forecast moves forward in time)~~ is the baseline uncertainty plus the uncertainty from the first forecasted day plus the second largest daily change observed during the forecast period from the last three years. We repeat this for the approximately 30 days of forecasted MMB. This implementation takes into account the larger variability (uncertainty) during the seasonal transition between the lower winter and higher summer discharge, or the smaller variability during the winter period.

7.2 Regions of interest (ROI)

~~Domain and ice mask alignment issues are non-trivial. In general, we~~ We work on the three different domains of the three RCMs, and expand the ROIs to match the RCMs (see Appendix E). However, some alignment issues cannot be solved. For example, we use BedMachine ice thickness to estimate BMB_{VHD} . Often, the largest BMB_{VHD} occurs near the ice margin under ice with the steepest surface slopes. This is also where the largest runoff often occurs, because the ice margin, at the lowest elevations, is exposed to the warmest air. If these RCM ice grid cells with high runoff are anywhere inside the BedMachine ice domain, that runoff is still included in our BMB_{VHD} estimates because it flows outward and passes through the BedMachine near-ice-edge grid cells with the large pressure gradients. However, if these RCM ice grid cells with high runoff are outside the BedMachine ice domain (ice thickness is 0), there is no reasonable way to include that runoff in our BMB_{VHD} budget. ~~It is ignored, and these grid cells are ignored.~~

550 The MAR ice domain is $1,828,800 \text{ km}^2$ of which $1,711,200 \text{ km}^2$ (94 %) are covered by the BedMachine ice mask, and $26,000 \text{ km}^2$ (6 %) are not. This 6 % area contributes ~15 % of the runoff (excluded from the VHD calculations) and likely

a higher percent of the VHD, because the border region of the ice sheet has the steepest gradients and the largest volume of subglacial flow.

555 We encourage RCM developers, BedMachine, and others to use a common and up-to-date mask (see Kjeldsen et al. (2020)).

7.3 Accumulating uncertainties

When accumulating errors as in Fig. 4, we use only the MMB ~~uncertainty. This is because the~~ and BMB_{GF} uncertainty. The MMB uncertainty is primarily due to unknown ice thickness and is invariant in time, and ~~for temporal accumulation, we treat the BMB and SMB uncertainties as random~~ the geothermal heat flux is steady state. SMB uncertainty is assumed to have errors
560 randomly distributed in time (for the purposes of Fig. 4). There may be time-invariant biases in the BMB_{friction} and SMB fields, but treating all uncertainties as biases is incorrect - evidence for that comes from the six other MB estimates. This distinction between bias and random uncertainty is only done for Fig. 4 where errors accumulate in time. The provided data product contains one uncertainty field and does not distinguish between systematic and random uncertainty.

The shaded region in Fig. 4 representing the uncertainty for This Study is computed as a 365 day rolling smooth from 1840
565 through 1999 of the above-described uncertainty, 1/365th of the annual error at now + 7 days, and a linear blend, from 2000 to now + 7 days, between the smoothed reconstructed uncertainty and the present and future more variable uncertainty.

The Mouginot et al. (2019), Colgan et al. (2019), and Kjeldsen et al. (2015) ~~all products~~ products all provide an error estimate, but do not distinguish between temporally fixed errors (biases; should accumulate in time) vs. temporally random errors.

570 We treat the Mouginot et al. (2019) data the same as This Study. Marine mass balance uncertainty is treated as a bias and accumulates, and surface mass balance uncertainty is treated as random and does not accumulate.

The Colgan et al. (2019) vs. this study bias and RMSE are ~~-50 and -69~~ -35 and 61 Gt yr⁻¹ respectively. This suggests that in any given year, there could be up to ~~-50 -35 ± 69 61~~ or ~~+1926/-119 -96~~ Gt yr⁻¹ departure from This Study. From this, we assign a ~~50 -35~~ Gt yr⁻¹ bias (~~42 -36~~ %; accumulates in time) and a ~~69 61~~ Gt yr⁻¹ RMSE (~~58 64~~ %; random in time).

575 The adjusted Kjeldsen et al. (2015) data have 0 surface and marine mass balance bias by definition (Sect. 5.4), but Fig. 4 displays the unadjusted data, and we ~~use the same method as for the Colgan et al. (2019) data. The unadjusted Kjeldsen et al. (2015) vs. this study bias and RMSE are -5 and -60 Gt yr⁻¹ respectively, meaning there could be up to a -5 ± 60~~ apply a 36 Gt yr⁻¹ departure from This Study. We assign a ~~5 Gt yr⁻¹ error to the accumulating data~~ accumulating uncertainty from the unadjusted MMB bias (Fig. 3).

580 7.4 Peripheral ~~Glaciers~~ ice masses

Greenland's peripheral glaciers and ice caps are not included in this product. Nonetheless, we briefly summarize recent mass balance estimates of these areas. ~~Greenland peripheral glaciers contribute~~ Greenlandic peripheral ice contributes more runoff per unit area than the main ice sheet – they are < 5 % of the total ice area but contribute ~15 to 20 % of the whole island mass loss (Bolch et al., 2013). From 2003 to 2009 and using the VC method (altimetry), Gardner et al. (2013) estimate -38 ± 7 Gt

585 yr⁻¹ peripheral mass balance. From 2006 to 2016 and using the VC method (DEM differencing), Zemp et al. (2020) estimate -51 ± 17 Gt yr⁻¹ peripheral mass balance, using Rastner et al. (2012) delineations.

~~When the IO estimate can be applied to these peripheral glaciers (i.e., thickness data becomes available) this product can then include them.~~

8 Results

590 From the 181 years of data, the mean mass balance is ~~-90-80 ± 120 Gt yr⁻¹~~ 125 Gt yr⁻¹, with a minimum of ~~-434-429 ± 109 Gt~~ in 2012 (SMB of ~~96-86 ± 9-8 Gt~~, MMB of ~~496-485 ± 51-46 Gt~~, BMB of ~~34-29 ± 7-6 Gt~~) and a maximum of ~~152 Gt in 1985-137 ± 83 Gt yr⁻¹ Gt in 1996~~ (SMB of ~~609-578 ± 74-52 Gt~~, MMB of ~~433-420 ± 34-39 Gt~~, BMB of ~~24-21 ± 12-5 Gt~~).

At the decadal average, the following trends are apparent. Surface mass balance has decreased from a high of ~450 Gt yr⁻¹ in the 1860s to low of ~260 Gt yr⁻¹ in the 2010s. SMB variability has also increased during this time. Marine mass balance
595 has increased slightly from a low of ~~~330-375 Gt yr⁻¹~~ in the 1860s to a high of ~~~500-490 Gt yr⁻¹~~ in the 2010s. Basal mass balance ~~has increased by ~15 % from a low of 24, from runoff as a proxy, had a high of 26 ± 16 Gt yr⁻¹ in the 1860s to a high of ~28-1930s and a low of 22 ± 5 Gt yr⁻¹ in the 2010s~~ 1990s, but as with runoff, is increasing in recent decades.

The total mass balance decadal trend from ~~1840 through 2020~~ the 1840s through the 2010s is one of general mass decrease and increased ~~inter-decadal~~ intra-decadal variability. The record begins in the 1840s with ~~~-20-10 Gt yr⁻¹~~, has only one (of 19)
600 decades with a mass gain ~~of ~40 (~50 Gt yr⁻¹ in the 1860s)~~, and a record low of ~~~-270-250 Gt yr⁻¹~~ in the 2010s.

9 Data availability

The RCM surface mass balance, ~~the marine mass balance~~, and the VHD basal mass balance components are updated daily, ~~and the marine mass balance approximately every 12 days, and all are~~ used to produce the final daily-updating product. The data area available at ~~while the paper is in review, and will be available at~~ <https://doi.org/10.22008/FK2/YG3IWC> (Mankoff et al.,
605 2021), with all historical ~~versions archived, after review~~ (daily updated) versions archived.

As part of our commitment to make continual and improving updates to the data product, we introduce a GitHub database (https://github.com/GEUS-Glaciology-and-Climatology/mass_balance/; last visited ~~2020-04-01~~ August 13, 2021) where users can track progress, make suggestions, discuss, ~~and~~ report and respond to issues that arise during use of this product.

10 Conclusions

610 This study is the first to provide a dataset containing more than a century and real time estimates detailing the state of Greenland ice sheet mass balance, with regional or sector spatial and daily temporal resolution products of surface mass balance, marine mass balance, basal mass balance, and the total mass balance.

IMBIE2 highlights that during the GRACE satellite gravimetry era (2003 through 2017), there are usually more than twenty independent estimates of annual Greenland ice sheet mass balance. Just two independent estimates, however, are available

615 prior to 2003. This study will therefore provide additional insight on ice sheet mass balance during the late 1980s and 1990s. IMBIE2 also highlights how the availability of mass balance estimates declines in the year prior to IMBIE2 publication. This reflects a lag period during which mass balance assessments from non-operational products are undergoing peer-review. The operational nature of this product supports the timely inclusion of annual MB estimates in community consensus reports such as those from IMBIE and the IPCC.

620 As such, the data products provided in this study present the first operational monitoring of the Greenland ice sheet total mass balance and its components. One property of the input-output approach used in This Study is the explanatory capabilities of the data products, allowing scrutiny of the physical origins of recorded mass changes. By excluding peripheral ice masses, this study allows and invites anyone to keep an eye on the current evolution of the Greenland ice sheet proper. However, as the spatial resolution of ~~RCM-increases~~RCMs increase and estimates of ~~ice thickness of the peripheral glacier peripheral~~ice thickness become available, our setup allows inclusion of these ice masses to generate a full Greenland-wide product. Moreover, as the determination of each of the individual components of the ice sheet mass balance is expected to improve over time through international research efforts, the total mass balance product presented will also be able to improve, as it is sustained by the Danish-Greenlandic governmental long-term monitoring effort – the Programme for Monitoring of the Greenland ice sheet (PROMICE).

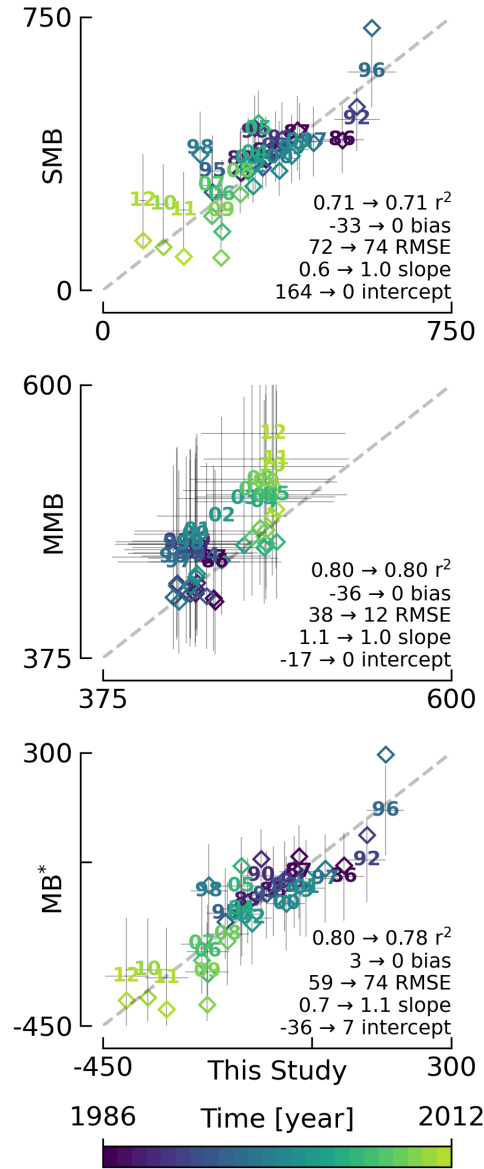


Figure 3. Comparison between This Study and the reconstructed (Kjeldsen et al., 2015) 27-year-overlap period. Numbers represent the last two digits of the years for the unadjusted data sets. The matching colored diamonds show the adjusted data. MB* shown here does not include BMB for either the reconstructed or This Study data. Arrows show statistical properties before and after the adjustment. No adjustment is made to MB*, but it is computed from Eq. 4 both before (numbered) and after (diamonds) the surface and marine mass balance adjustments.

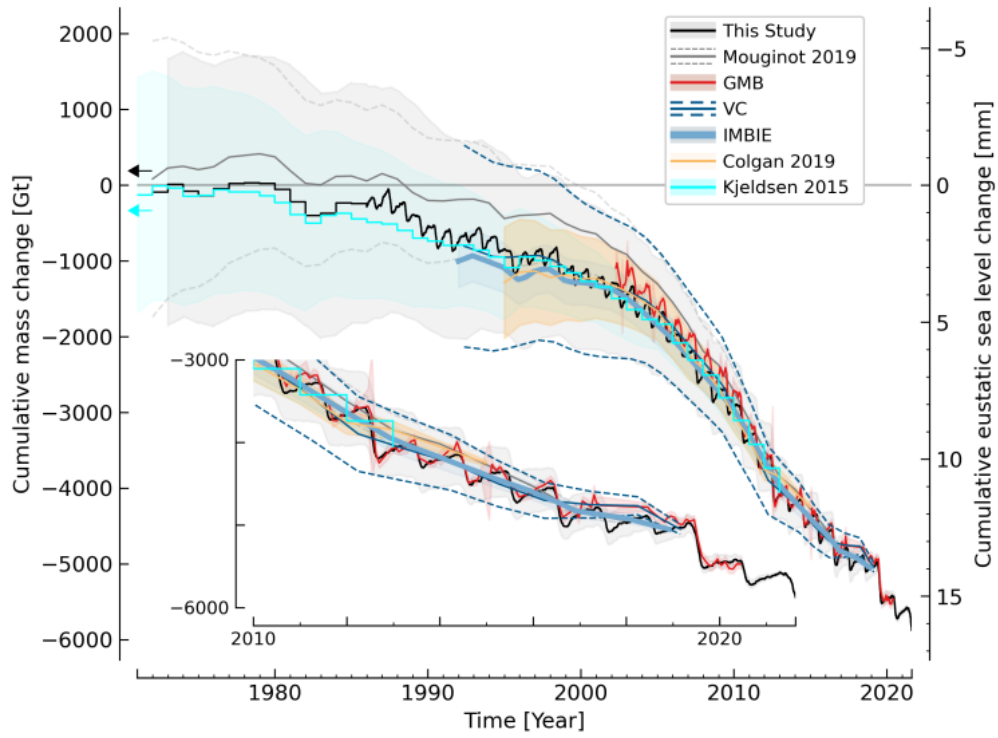


Figure 4. Comparison between This Study and other mass balance time series. Note that various products do or do not include basal mass balance or peripheral [glaciers ice masses](#) (see Table ??2). This Study annual-resolution data prior to 1986 is the Kjeldsen et al. (2015) data adjusted as described in Sect. 5.4. Sea level rise calculated as $-Gt/361.8$. Inset highlights changes since 2010.

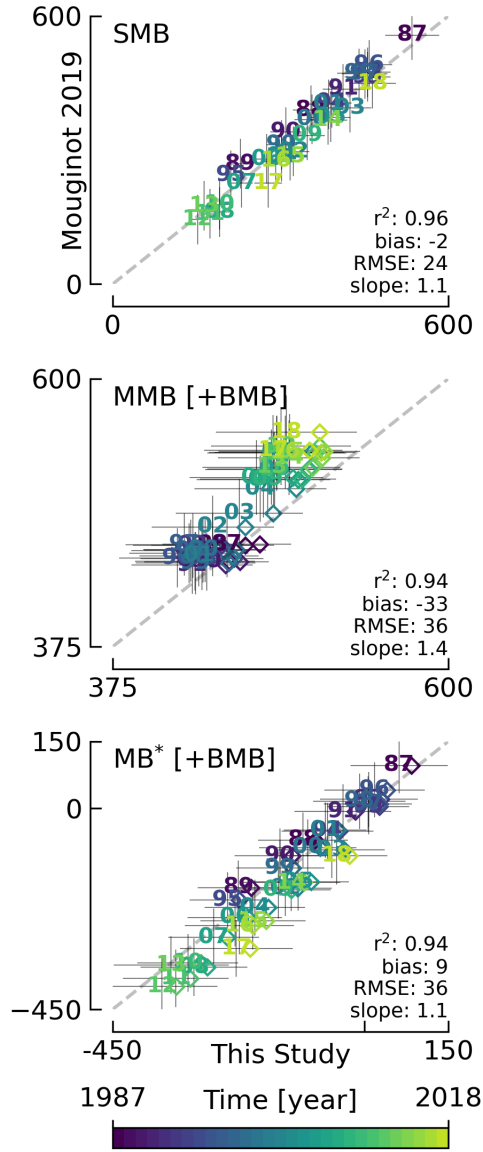


Figure 5. Comparison of This Study vs Mouginot et al. (2019). Numbers-All axes units are Gt yr^{-1} . Plotted numbers represent the last two digits of the year. Matching colored diamonds show the data when BMB is added to This Study. Printed numbers (r^2 , bias, RMSE, slope) compare values without BMB.

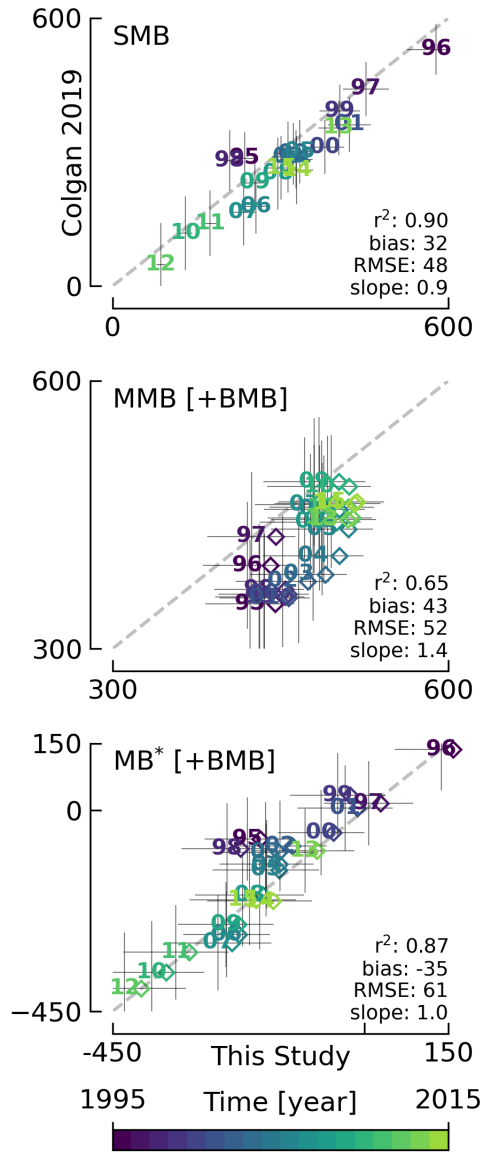


Figure 6. Comparison of This Study vs Colgan et al. (2019). **Numbers**-All axes units are Gt yr^{-1} . **Plotted numbers** represent the last two digits of the year. Matching colored diamonds show the data when BMB is added to This Study. Printed numbers (r^2 , bias, RMSE, slope) compare values without BMB.

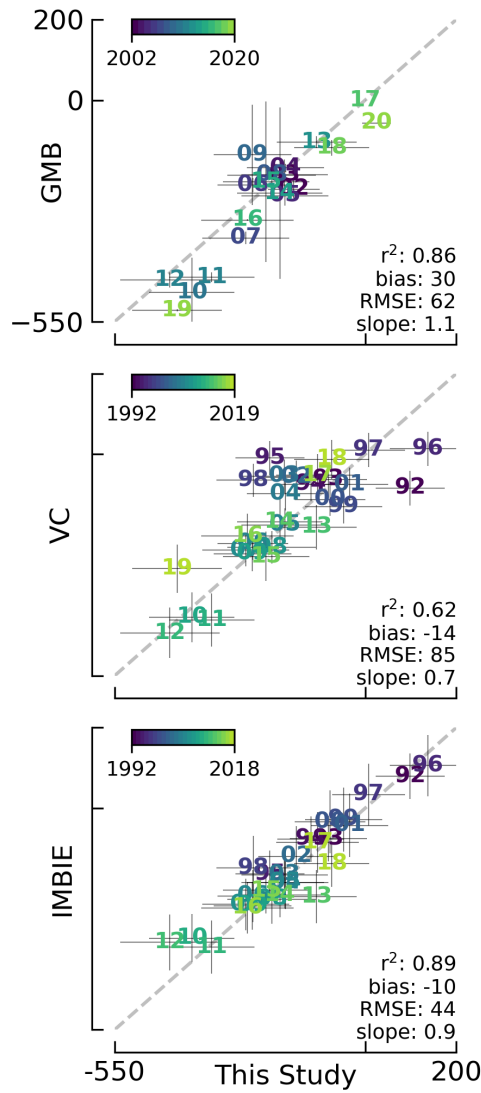


Figure 7. This Study total mass balance (MB) vs. the gravimetric method (GMB), volume change method (VC) and IMBIE2 estimates of MB. All three include BMB. All axes units are Gt yr^{-1} . Plotted numbers represent the last two digits of the year. GRACE and IMBIE2 include peripheral glaciers ice masses.

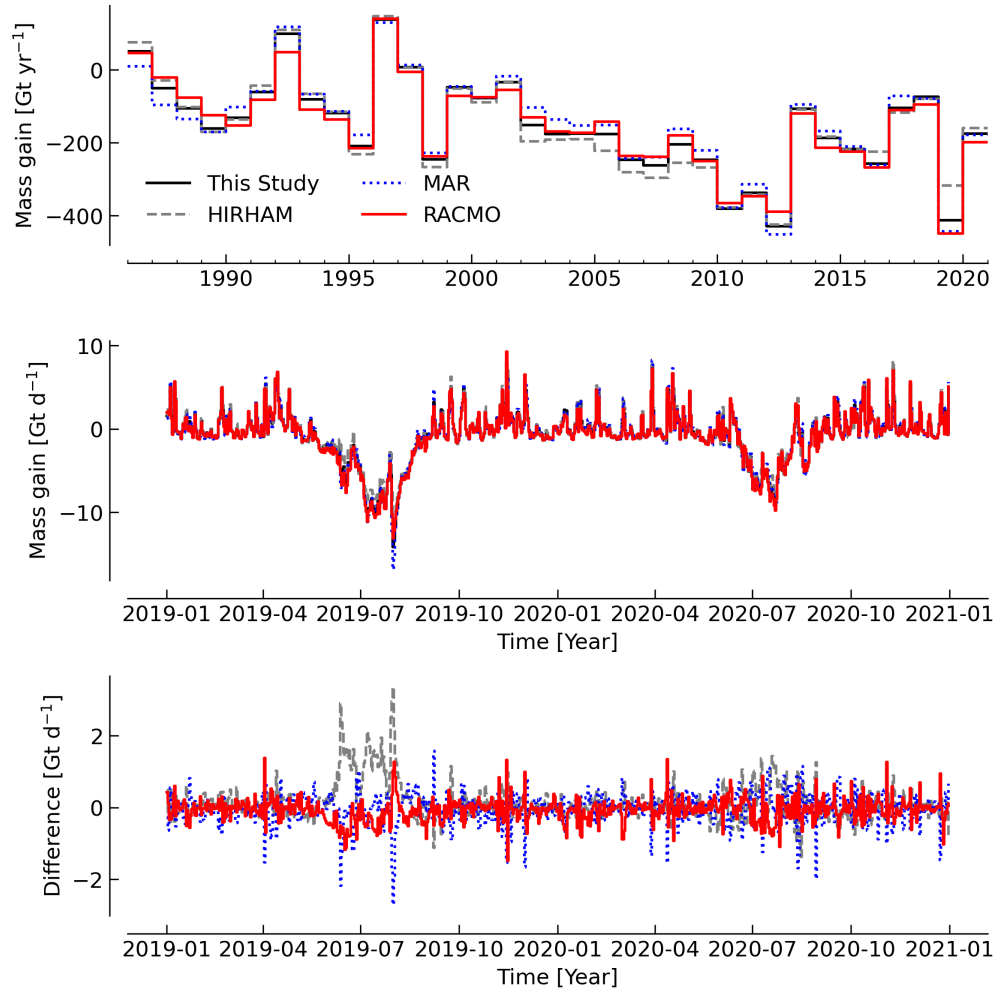


Figure A1. Comparison of This Study combined RCM product and the HIRHAM/HARMONIE, MAR, and RACMO RCMs. Results shown here are MB, not SMB, but the same MMB and BMB have been subtracted from each SMB product. Top panel: annual MB for entire time series. Middle panel: Example two years (2019 and 2020) at daily resolution. Bottom panel: Difference between the three RCM MB products and This Study RCM-averaged product, for the same data shown in the middle panel.

Appendix B: Mouginot 2019 by region

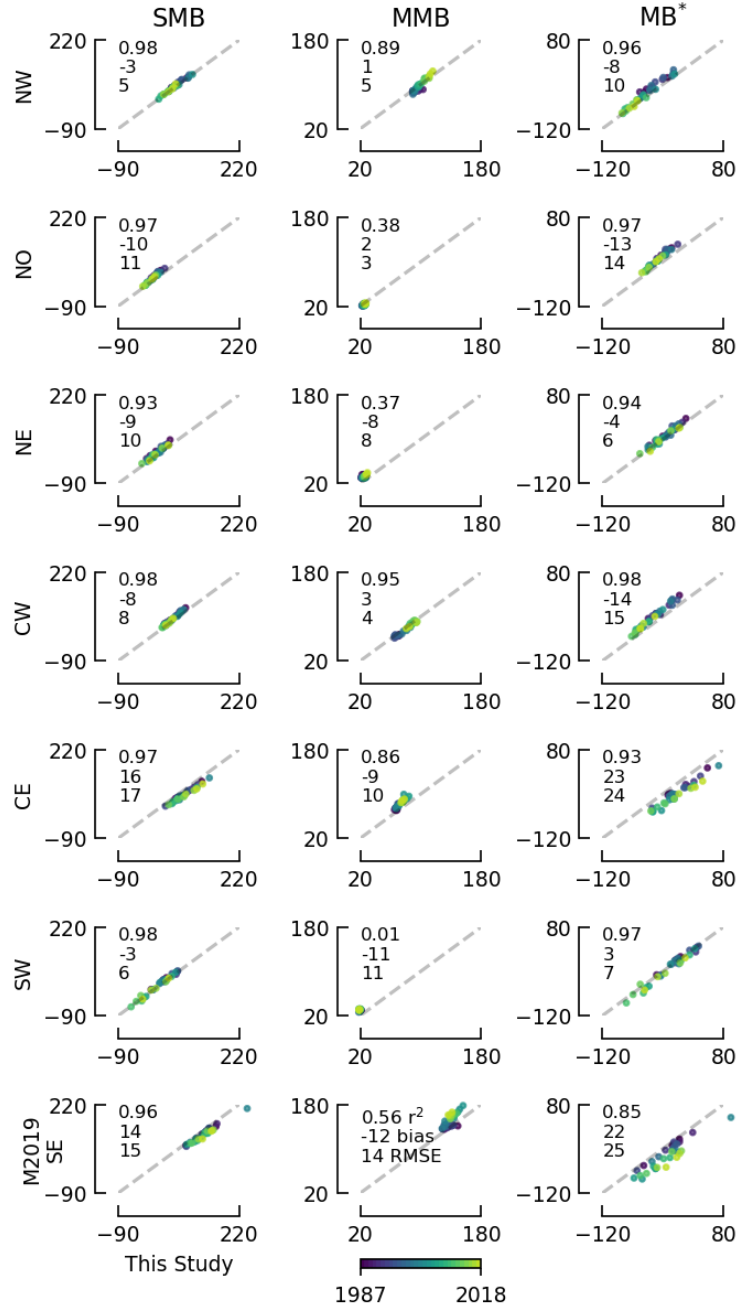


Figure B1. Comparison between This Study ([excluding BMB](#)) and Mouginit et al. (2019). Same data and display as Fig. 5 except here displayed by Mouginit and Rignot (2019) region. Numbers in each graph show r^2 , bias, and RMSE, from top to bottom, respectively. [All axes units are \$\text{Gt yr}^{-1}\$](#) . [Plotted numbers represent the last two digits of the year.](#)

Appendix C: Colgan 2019 by sector

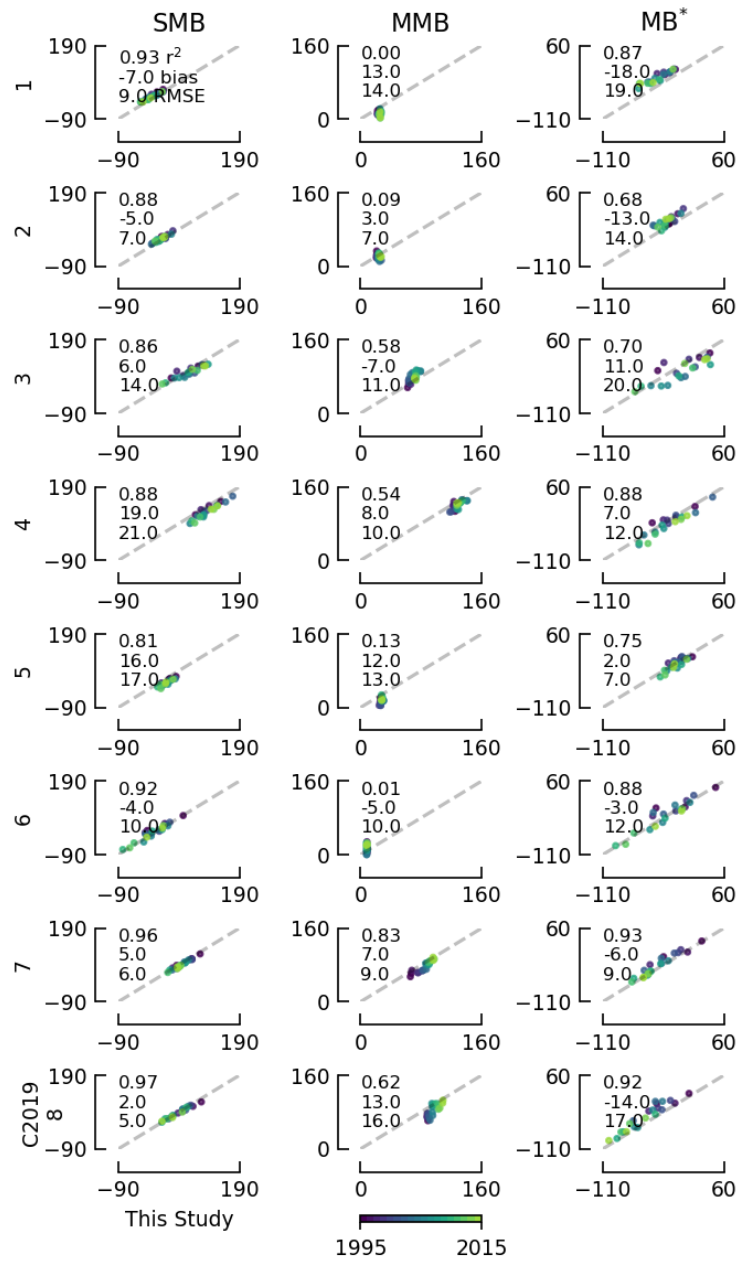


Figure C1. Comparison between This Study (excluding BMB) and Colgan et al. (2019). Same data and display as Fig. 6 except here displayed by Zwally et al. (2012) sector. Numbers in each graph show r^2 , bias, and RMSE, from top to bottom, respectively. All axes units are Gt yr^{-1} . Plotted numbers represent the last two digits of the year.

Appendix D: Reconstructed runoff

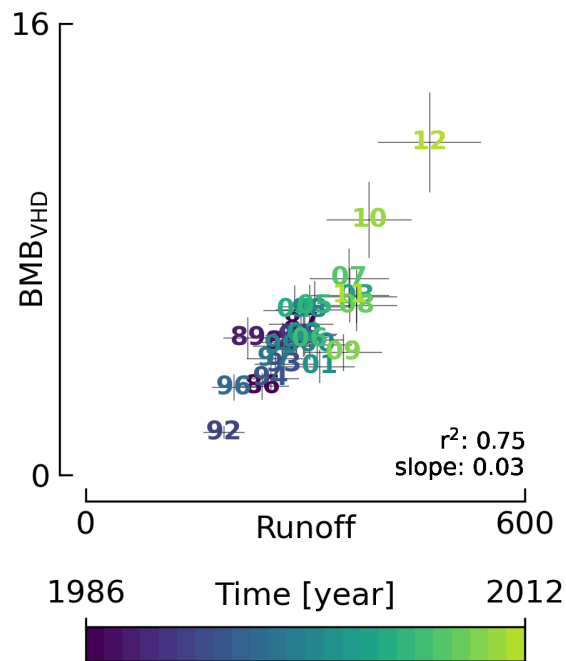


Figure D1. Comparison between MAR runoff and basal viscous heat dissipation derived from that runoff. The slope is used to estimate the reconstructed BMB_{VHD} from reconstructed runoff (see Sect. 5.3). Axes units are Gt yr⁻¹. Plotted numbers represent the last two digits of the year.

Appendix E: [RCM coverage](#)

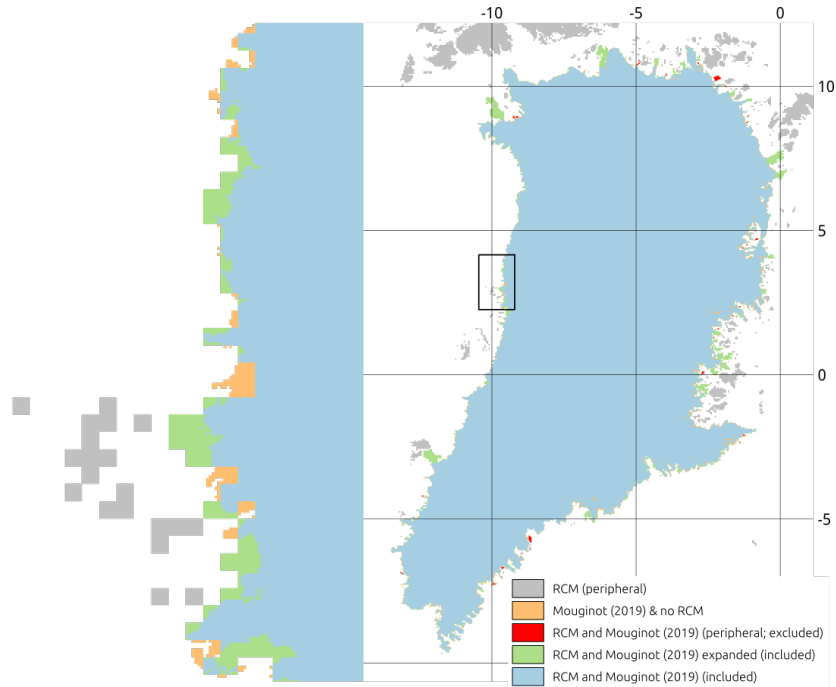


Figure E1. [HIRHAM RCM coverage by Mougnot and Rignot \(2019\)](#). Coverage of HIRHAM by Zwally et al. (2012), and MAR and RACMO by Mougnot and Rignot (2019) and Zwally et al. (2012) is similar to graphic shown here (See section 5.5 for discussion of RACMO coverage issues). HIRHAM latitude and longitude covers the equator because we work on the native HIRHAM rotated pole coordinate system.

635 Appendix F: Software

This work was performed using only open-source software, primarily GRASS GIS (Neteler et al., 2012), CDO (Schulzweida, 2019), NCO (Zender, 2008), GDAL (GDAL/OGR contributors, 2020), and Python (Van Rossum and Drake Jr, 1995), in particular the Jupyter (Kluyver et al., 2016), dask (Dask Development Team, 2016; Rocklin, 2015), pandas (McKinney, 2010), geopandas (Jordahl et al., 2020), numpy (Oliphant, 2006), x-array (Hoyer and Hamman, 2017), and
640 Matplotlib (Hunter, 2007) packages. The entire work was performed in Emacs (Stallman, 1981) using Org Mode (Schulte et al., 2012) on GNU/Linux and using many GNU utilities. The parallel (Tange, 2011) tool was used to speed up processing.

Appendix G: CRediT

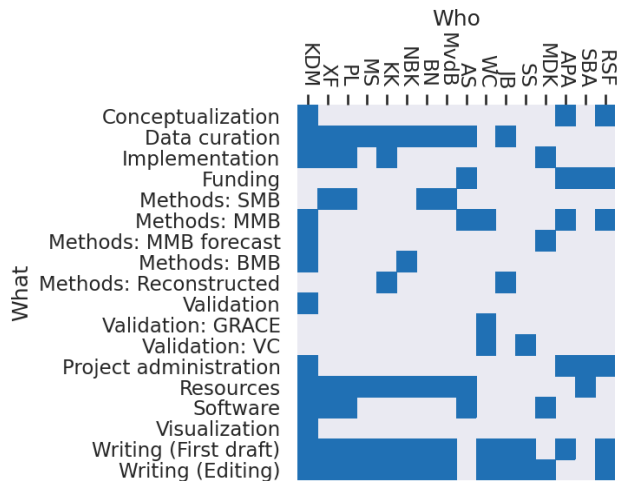


Figure G1. Author contributions following the CRediT system (Allen et al., 2014; Brand et al., 2015; Allen et al., 2019)

Author contributions. { Author contribution is captured following the CRediT system (Allen et al., 2014; Brand et al., 2015; Allen et al., 2019) and shown graphically in Figure G1. The following authors contributed in the following ways. Conceptualization: KDM, APA, and RSF. Curation: KDM, XF, PL, MS, KK, NBK, BN, MvdB, AS, and JB. Implementation: KDM, XF, PL, KK, and MKD. Funding: AS, APA, SBA, and RSF. SMB methods: XF, PL, BN, and MvdB. MMB methods: KDM, WC, AS, MKD, APA, and RSF. BMB methods: NBK and KDM. Validation (general): KDM. Validation GRACE: WC. Validation VC: WC and SS. Reconstruction methods: KK, JB, and KDM. Project admin: KDM, APA, SBA, and RSF. Resources: KDM, XF, PL, MS, KK, NBK, BN, MvdB, AS, and SBA. Software: KDM, XF, PL, AS, and MKD. Visualization: KDM. Writing: KDM, XF, PL, MS, KK, NBK, BN, MvdB, WC, JB, SS, APA, and RSF. }

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. The editor, one anonymous reviewer (Anonymous, 2021), and Andrew Shepherd (Shepherd, 2021) provided feedback and helped improve this paper.

Financial Support: Funding was provided by the Programme for Monitoring of the Greenland ice sheet (PROMICE). Parts of this work were funded by the INTAROS project under the European Union’s Horizon 2020 research and innovation program under grant agreement no.

727890. B. Noël was funded by the NWO VENI grant VI.Veni.192.019. [MvdB acknowledges support from the Netherlands Earth System Science Centre \(NESSC\).](#)

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