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.**

Contents

1 Summary

We are grateful for the helpful reviews and pleased that the reviewers seem to think this is useful work. We would like to warn and apologize to the reviewers that due to their helpful comments, the document has changed substantially - enough that while the LaTeXdiff program did not crash, it does not produce very useful results. This significant re-write means that some of the specific comments below cannot be directly addressed because some text and figures have been entirely removed, and that a second round of review may be a bit more work than if we had only done the minimum needed to address the comments. We hope you don't mind this extra work and see the value in the changes that we made. Thank you.

2 Review 1

2.1 Summary and General Commments

A high-resolution product of liquid discharge from the Greenland Ice Sheet (GrIS) and the unglaciated area of Greenland is derived for the period 1979 – 2017 and provided with various static hydrological quantities (e.g. basins and outlet locations). Gridded runoff is taken from two regional climate models (RCMs) simulations (MAR and RACMO), whose output is statistically downscaled to a horizontal resolution of 1 km. Hydrological characteristics (e.g. basin delineation) are computed from surface elevation according to ArcticDEM. BedMachine surface and bed elevation data is additionally considered to assess the sensitivity of the routing network to uncertainties in surface topography and to consider subglacial ice sheet drainage.

This study addresses a very relevant topic, namely the quantification of liquid discharge from Greenland in the current climate and specifically the locations where this freshwater will enter the ocean. It closes the link between RCM simulations, which provide gridded runoff at increasingly higher horizontal resolution and the need for (high-resolution) liquid discharge locations, which are not directly provided from RCM simulations. The manuscript is well written but the structure needs some improvements in my opinion. Additionally, certain topics (particularly methods) are not explained with enough details.

We're happy to read that reviewer 1 thinks the topic is relevant, and this work "closes links" and is well written. Reviewer 1 has also provided an extremely detailed review. We respond to all comments below.

2.2 Major Comments

2.2.1 1) Improve structure of manuscript

In my opinion, the manuscript lacks a clear structure, as e.g. introduction of data and applied methods are not restricted to the data and methods sections but also appear e.g. in section 6. Furthermore, the partitioning of subtopics in results and discussion (sections 5 and 6) does not seem logical to me. I would suggest the following structure:

```
1. Introduction
2. Input and validation data
2.1. Downscaled gridded RCM data (part of current section 2)
2.2. Time-invariant data (DEMs, ice/ocean masks) (part of current section 2)
2.3. River discharge observations (part of current section 6.2)
3. Methods
3.1. Masks and grid cell alignment (current section 3.1)
3.2. Derivation of hydrological quantities (e.g. basins, outlet locations, etc.)
     (see next major comments for more details about the content of this section)
     (current section 3 and part of current section 6.3.1)
4. Product evaluation and assessment
4.1. Main characteristics (current section 5)
4.2. Comparison with previous similar work (current section 6.1)
4.3. Validation/Comparison of product with observational river discharge
     (current section 6.2)
4.4. Product uncertainties (current section 6.3)
```

```
4.5. Remaining sources of freshwater input in fjords (current section 6.4)
5. Technical product description and data/code availability
5.1. Product description (current section 4)
5.2. Data and code availability (current section 7)
6. Conclusions
```

We have re-arranged the document into roughly the order that you suggest.

2.2.2 2) Missing parts in method section

The method section should be extended – particularly the part about the derivation of the hydraulic characteristics. Specifically, I miss information about:

- How were (artificial) depressions in the DEM handled? With a filling algorithm?

Correct re filling algorithm. This was not described in the submitted manuscript because the routing and filling algorithms are standard GIS tools. We've added a sentence explaining that sinks are filled so that all water is routed to leave the domain.

- I'm confused about the applied flow direction algorithm. Was a single flow direction (SFD) or a multiple flow direction (MFD) algorithm used? And how were the basins delineated if a MFD algorithm was used (which has a dispersive character)?

We used SFD-8.

Moreover, the method used for assessing the basin uncertainty (section 6.3.1) should be moved to this section. It should include a more detailed discussion of the equation used to compute the hydraulic head and how this equation is applied to derive the sensitivity experiments in the appendix (with various subglacial pressure).

We now only perform subglacial not supraglacial routing. Discussion about sensitivity experiment is now re-written into methods. Results are now discussed in result section, not appendix.

2.2.3 3) Sensitivity of basins delineation to uncertainties in surface elevation and partitioning of surface/subsurface runoff

The evaluation of the Kangerlussuaq / Watson river catchment with river discharge data reveals that the accurate basin delineation is crucial. The sensitivity experiments with a different DEM for the surface and the consideration of subglacial drainage are thus extremely interesting and useful. I wonder if the uncertainty in the basin delineation, which is illustrated in the appendix, could be translated to runoff uncertainties (and be included in the runoff output product). One could for instance compute discharge at all (coastal) outlets for all sensitivity experiments and check the range in obtained runoff. This work would reveal catchments for which runoff quantifications are more (un)certain. It's probably not necessary to include these runoff uncertainty values in the current product but it would be nice upgrade.

We have moved this sensitivity section into results rather than appendix. Unfortunately even these sensitivity experiments do not capture what we believe to be the "true" Watson basin (see Lindbäck et al. (2014) and Lindbäck et al. (2015)). We now manually select those "southern" basins to show that when included the modeled runoff matches the observed.

We now provide subglacially routed water (for $k = 1.0$) rather than supraglacially routed water, as this better reflects reality. We generate subglacial routing for $k \in [0.8, 0.9, and 1.0]$ and use that for the sensitivity experiment. We also created a revision with $k \in [0.70.8, 0.9, 1.0, 1.09]$ (where $k = 1.09$ is effectively surface routing) but the paper became too complicated covering all those edge cases, 0.7 and 1.09 are extreme values, and releasing even 3 product for $k \in [0.8, 0.9, 1.0]$ seems unhelpful to end-users. We opted instead to briefly use the 3 k scenario for the sensitivity experiment, but only discuss results from $k = 1.0$ and release that data.

As for using this simple sensitivity experiment to quantify runoff uncertainty - we are not sure how to do that. In the expanded Uncertainty section we now discuss the complexity of quantitatively estimating runoff uncertainty and how the basin uncertainty is not directly related, and even defining or comparing ice basins between k scenario is difficult. For land runoff, the outlet is fixed. As you suggest we can and do take different k simulations for upstream ice, route to a fixed land outlet, and look at the range of runoff from that outlet. The difference between $k = 0.8$ and $k = 1.0$ is minor - much less than the differences between RCMs, or an RCM and observations. Doing this for ice outlets is significantly more complicated because the basins and outlets change for each k simulation, so it is not clear what should be compared between simulations.

It is a tractable problem to do manually for one or a few outlets. We provide the streams, outlets, and basins for $k \in [0.8, 0.9, 1.0]$, so that users can see possible changes in basin size, but only runoff for $k = 1.0$ to make the end-product simpler to use.

2.3 Minor Comments

2.3.1 Content-related (text)

Page 1 line 10: "contributes an additional ~35% to the ice runoff " → confusingly stated (because the ~35% are referring to the total runoff I guess) → rephrase

We have removed this text and the discussion between ice and land runoff.

P2L26-28: I don't understand to what "satellite basemap imagery" is referring to. To the ocean mask?

This was referring to the background satellite image in the map graphics of the basins for each observational data set. I have removed this text from this section of the document, but keep the "Basemap from Howat et al. (2014); Howat (2017a)" in each figure where the data is used, as per ESSD policy. I disagree with this policy.

P2L29: Mention somewhere here that RACMO only provides runoff for the glaciate area of Greenland

RACMO now includes land runoff, expands back in time to 1958, and both RACMO and MAR forward in time to 2019.

P3L5-7: The runoff downscaling should be explained in more detail (or a reference for the procedure should be provided)

References added.

P3L8: Is it justified to assume that the firn layers in both simulations (MAR and RACMO) are in approximate equilibrium in 1979 (i.e. was there a spin-up performed or when did the simulations start?)

Yes, spin-up occurred prior to results being provided here.

P3L14-17: How are (artificial) inland depression treated that would lead to erroneous inland outlets. Are such depressions apparent in the DEM? And if so, how are they removed?

All depressions are filled until runoff leaves the domain (ice margin for ice runoff, coast for land runoff). This is now clarified in the text.

P3L15: I'm confused by the part "multi-flow direction from eight neighbors". Does it imply that a multiflow direction algorithm with dispersion was used? Or a D8 algorithm (because this algorithm also allows flow from (maximal) eight neighbors).

Multi-flow can come in from 8 neighbors, but only leaves to one. The text has been clarified.

P3L26-27: I'm not sure if I understand this sentence correctly: so land pixels surrounded by ice are set to ice (but their elevation is left unchanged)?

Correct. These local bumps may impact local streams, but should have no other effect because results are reported at the outlet, and the bumps are internal to basins, or if they define basin boundaries they still do even if their classification has changed. Put differently, inland ice streams often terminate (incorrectly, we presume) at nunatuks. We therefore set nunatuks to type 'ice' for the routing so that everything is routed to the ice margin. We then reclassify as 'land' so that the ice basin is not artificially enlarged for the runoff estimates.

We now explicitly point out that streams in the ice domain are merely "representative" of the model streams, but do not likely reflect actual subglacial streams, unlike the land streams which do appear to follow actual streams when compared against satellite imagery.

P4L18-20: I don't understand this part: Is the downscaled gridded runoff data provided on an EPSG:3413 map projection (because I guess the direct output from the RCMs is on a rotated lon/lat-grid)? And the EPSG:3413 projection is based on WGS 84 (and thus an ellipsoid). But some data is provided in a coordinate system based on a sphere (earth spheroid)?

I'm not entirely sure about the internal model grids - some are on a rotated pole lon/lat grid. They are provided to me on a EPSG:3413 projection. In EPSG:3413 1 m^2 is not equal to 1 m^2 in the real world, because of projection errors. We scale the data to account for this scale effect.

P4L22-23: It should be stated in this section that land quantities (e.g. basin polygons and runoff) also include the same quantity from the glaciated part (I assume). So I guess runoff from land contains both runoff from the unglaciated and the glaciated part?

The land runoff only include runoff that originated on the non-ice-covered land. In the data set you saw with the initial submission, land polygons included the

upstream ice area. In the current version we provide both the polygons with the upstream ice area, and the polygons cropped to only the ice-free land area, which is where the RCM land runoff is partitioned.

Including the land basins with upstream (under-ice) included is useful so that a point placed on the ice can easily determine which land basin contains the land outlet.

P5L8-10: Why are the more larger land basins than ice basins? Do the land basins incorporate the ice basins?

Yes - in the first version the land basins incorporated the ice basins, but land runoff was only calculated from the MAR land cells over the ice-free land portion of those basins. Land basins have to include the ice basins at some point in the processing because otherwise the routing algorithm will treat the ice edge as the edge of the domain, route streams there, and place outlets there. Having the land domain include the ice area forces outlets to the ocean boundary.

In this revised version we now crop the land domains to the ice-free portion after the routing algorithm step.

P5L20-22: It should be more clearly stated in this sentence that the 4380 m3 refers to runoff from a single basin.

Sentence removed.

P5L24: I assume the ±30 km3 represent the RCM runoff uncertainty of 15% (this should be clearly stated here). And shouldn't it rather be ±60 km3? And how is this value of 15% derived (is there a reference)? I think it would be useful to mention this uncertainty value already in section 2 (input data).

This sentence removed at the suggestion of reviewers. Annual runoff is not the point of this work. But we did add a sentence about RCM uncertainty when we introduce the data. You are correct that errors of X % should have been ± X, not ± (X/2)

P6L8-11: This sentence does not belong here but rather in section 6.3.1. Furthermore, I find the sentence a bit hard to understand (particularly the last part) – could it be rephrased? It states that flow-path derived from the ArcticDEM generally agree better with satellite images than flow-path derived from BedMachine data, right?

Correct, clarified, and moved.

P6L17: Could you explain the reason why the increase in spatio-temporal resolution increases the signal-to-noise ratio in more detail? And I would include a reference to section 6.3.4 here (so that the reader knows where this strategy is discussed in the manuscript).

More detail added and reference to Mitigation section where it is discussed even more.

P6L18-26: I would move this part to the data section (2).

Done - and in table form.

P7L33-34: "MAR runoff slightly overestimates the GEM observations early in the year, and slightly underestimates the observation late in the year" → this is an interesting finding and probably related to storage of water in the (un-)glaciated area of the basin on intraannual time scales

It may be interesting, but it is no longer in the revised manuscript. Given the additional observational data sets we now show all data from only the last year of each data set. This feature is no longer apparent and is not discussed in the revision.

MAR has been updated (v3.9 to 3.11) and I don't think this interesting artefact is there but not being show. It would show up in the scatter plots if it exists, and I don't see it there (consistently).

P8L3-4: This step-like change in MAR runoff is rather strange. Are you certain that this is not an artefact (e.g. caused by an issue in MAR, the statistical downscaling procedure of runoff or the alignment of the 1 km and the 100 m masks)?

We no longer see this feature. We are using now MAR 3.11 instead of 3.9, which may also be one reason it has disappeared.

P8L27: "slight lag between models signals and the observations." → could this time lag be related to the neglect of routing travel time?

Perhaps. We now focus more on bulk analysis, and use what we think are more appropriate graphics than a time-series, although the time series is still included.

P8L28-29: What is the reason for the significantly higher temporal variability in RACMO? Could this be linked to the different treatment of liquid water retention on bare ice between the RCMs?

In the revised manuscript MAR has been updated from 3.9 to 3.11, and RACMO now includes land runoff. This artefact is no longer present.

P9L1-5: Why was the existing proxy data not used for further model validation (if it exists)?

We have remove this text. This proxy data is a bit far removed from the models to be useful for validating them - turbulent plumes exist and must be modeled. The more likely scenario is that this product released here is used as inputs to those downstream studies. Indeed, that is what has happened in the past, but each study needed to do the work done here, wasting effort.

P9L12: There is no equation 1

There is, but we only referred to it immediately around it, and therefore did not reference the number (1). That has been changed.

P9L15: "because large volumes of runoff usually come from large areas." → I do not understand this part of the sentence, could it be rephrased?

"areas" should have been "basins". Sentence no longer in revised text.

P10L4-5: What is meant by "hydraulic jumps"? I guess not the physical phenomena in hydraulics. If not, this term should be replaced to avoid ambiguity.

That is the precise meaning. This occurs when masks are misaligned. Whenever the Citterio et al. (2013) ice mask transitions from ice to land, if BedMachine ice thickness is not 0, then the system transitions from subglacial to land surface in an abrupt fashion. There will be something unrealistic - either a waterfall or a sink that needs to be filled and may flow out somewhere else. There are many small basins along the coast and ice margin and many of these are realistic, but some may be due to the mask issues described above. This is discussed in more detail in the revised text.

P10L11: This equation (and the corresponding text) should be moved to the method section.

Now rewritten because we only use subglacial routing. This equation and the description of subglacial routing is moved up to the Methods section.

P10L17-19: I find the transition between the previous and this part a bit strange. The part before explains how routing and basin delineation is derived when bed elevation is considered (this part should anyway be explained in the methods section in my opinion) but this section compares basin delineation based on two different surface topographies.

This text has been removed.

P10L30: Can you provide a reference for this value of 15%? Also, this value should already be mentioned in the data description (section 2).

Additional text and reference added. Value introduced in the Methods section. More text in the RCM Uncertainty section.

P11L4-5: Replace "highlighted above" with reference to relevant section. Additionally, are you certain that the step-like changes in RCM runoff originates from the actual RCM simulation (and is not generated by the subsequent postprocessing steps (e.g. downscaling or grid cell alignment).

Text removed.

P11L15: "current limitation" → future RCM simulation will still only capture features and process of certain spatial scales. But do you think that the most crucial scale will be represented in these simulations with higher resolution?

Text removed, but yes, I think when the RCMs are run at 1 km or 100 m they'll do well enough. I think they do already (depending on your use case) after seeing the agreement between RCM and observations here.

P12L4-5: Can you provide a reference that supports this (net storage is approximately zero) assumption?

I cannot, but have made the statement less certain.

P12L21-23: This sentence should be rephrased or removed. Making a prediction about fjord precipitation from the Greenland-wide fraction of land runoff is not reasonable in my opinion.

Removed.

P13L6-7: "perhaps due to temporal directionality" $\rightarrow$ I don't understand this part

Removed. Time moves in one direction (?) so we cannot cite papers that have not yet been written, or document bugs we have not yet found. We use the GitHub website for this work to note those papers and issue that arise after publication.

P13L7: Is "version of the dataset" meant here?

Both. The document, code, and dataset from that code are all versioned to the same GitHub hash. Parts of this document write itself, using the data it generated. The NetCDF files also have the git hash. We prefer to leave the sentence as-is. The document has a git hash. The dataset has a git-hash for an earlier version of the document. If you compare changes between the dataset has and the current document hash, changes only occur in the text portions of the document (that are exported for the journal to publish) not the code portions of the document that generated the data set, or the code changes don't impact the data values (for example, only changes to metadata or file location).

P13L20: Again, are the stated uncertainty values correct?

We've doubled the errors - they are now ± 15 %, not ± 7.5 %. Not shown, but discussed, when time series plots show the ± 15 % from all three k scenario, differences in runoff from k are « differences between RCMs or between RCM and observations.

2.3.2 Typos, phrasing and stylistic comments

Page 1 line 10: Change "over the time series" to "over time"

Sentence changed.

P2L4-5: I don't understand the meaning of this sentence ("Immediately upstream from...") – isn't it obvious that no submarine melting occurs upstream of the grounding line?

Sentence changed.

P3L12-13: "Each outlet has one upstream basin and each basin has one outlet" $\rightarrow$ I don't understand the meaning of this sentence, isn't this fact obvious?

Removed.

P3L22: Change "100 m2 pixel" to "10,000 m2 pixel"

Change to "100 m x 100 m pixel"

P4L12-13: "In the case of a small basin," $\rightarrow$ this sentence is a bit oddly stated – could it be rephrased?

Rephrased.

P4L30-31: I would remove "four per year" (and optionally change "provided as annual NetCDF files" to "provided as four annual NetCDF files").

Done.

P5L6-7: “Runoff ice products. . . ” → oddly stated sentence → rephrase

Rephrased. Also, we now use "discharge" to refer to our product, to keep it distinct from the source of the water, which is runoff from the RCMs.

P5L21: “2012-08-06” → write date out

Sentence removed.

P5L27: “contributes an additional 35% to the ice runoff” → again, I find this a bit confusingly stated (I guess the 35% refer to total liquid runoff?). Maybe better: “contributes 35% to total runoff”

Sentence removed.

P6L5: Maybe change “and additional data products.” to “and is provided with additional data.”

Done.

P6L23: change “results to all observations that we have been able to find that are publicly accessible” to “results to all publicly accessible observations we could find”

Done.

P7L1: change “with high melt or runoff; Basin” to “with high runoff (and associated melt): Basin”

Done.

P7L7: change “include ice to the south of itself” to “include a glaciated area to the south”

Reprhased.

P7L23: “and a without an ice basin does have RCM ice cells” → odd formulation → rephrase (e.g. change “without an ice basin” to “unglaciated”

Rephrased.

P8L11-12: Rephrase sentence, e.g. to “The MAR relative runoff bias ranges from -20% (last day of time series) to +140% (28 July).”

Text removed, but we now discuss biases much more extensively.

P8L25: change “models than the observations” to “models than in the observations”

Text removed.

P8[edit: 9]L7: change “discussed below” to “still discussed in Sect. 6.3.2.”

Done.

P8[edit: 9]L8: change “source uncertainty – the routing model, which exhibits in two different ways: Spatial (basin delineation) and temporal (runoff delay)” to “source of uncertainty – the routing model, which generates both spatial (basin delineation) and temporal (runoff delay) uncertainty”

Done.

P9L10-11: Rephrase to e.g.: "Temporal uncertainty is not systematically addressed in this work but a method to reduce it is discussed in Sect. 6.3.4."

Rephrased.

P10L19-20: Change sentence to e.g. "Results from additional sensitivity experiments (with different input data and hydraulic head computations) are shown in the Appendix."

This section rewritten and moved.

P10L29: rephrase "they do not precisely nor accurately capture reality" to e.g. "they represent reality discretised and simplified."

Done.

P12L11: change "That ice downstream" to "The downstream ice"

Done.

P12L26: Change "are approximately steady state" to "are approximately in steady state"

Done.

P12L30: Replace "GIS-wide ice sheet surface runoff" with "Greenland-wide ice sheet surface runoff". Otherwise, "GIS" is used both for "Greenland Ice Sheet" and "Geographical Information System"

Sentence removed, but we are more careful with our use of GIS.

P13L2: Replace "This work in its entirety is available" with "Output data of this work and part of the discharge observations are available"

Rephrased.

P13L8-9: This sentence is a bit oddly stated. Could you rephrase it?

Paragraph removed.

P13L12-15: This sentence is rather complicated to read and understand. Could you rephrase it?

Paragraph removed.

P13L15: change "differences in needed" to "differences are needed"

Paragraph removed.

P13L21: change "displaying and overall increase in both magnitude and variability" to "an overall increase in both its magnitude and variability"

Sentence removed.

P13L22: change "scale" to "scales"

Done.

2.3.3 Figures and Tables

Figure 1: Change caption to: "Overview showing ice basins (blue), land basins (green) and locations of following map figures (black)."

Figure modified and caption changed.

Figure 2: Change "Sec." to "Sect." in caption (also other occurrences)

Figure removed, but we use "Sect." everywhere now.

Figure 3: What is meant with "(this)" in the caption?

Figure removed, but "this" was referring to this product, not 3rd party products.

Figure 4: Maybe the error bars should be removed from this figure to improve readability. Additionally, "(this product based on ArcticDEM basins in Fig. 5)" should be rephrased.

Figure simplified and combined with following figure.

Figure 5: It's difficult to distinguish between different basins in this plot. Maybe readability could be improved by only plotting the basin's boundaries (without hatching). Could you also plot the Lindbäck et al. (2015) basin and the one you used to produce the right panel of figure 4?

Figure simplified and combined with previous figure.

Figure 6: A reference to this figure only appears in section 6.3.1, so its number and position should be changed accordingly. The legend is hard to read (it could be moved outside of the map area). Additionally, I would remove the sentence: "Region is zoomed in near Sermeq Kujalleq (Jakobshavn Isbræ)."

Figure removed.

Figure 7: Change "Fig. 10" to "Fig. 10 and 11" and "visible is basin artefact" to "visible is a basin artefact". Is the "RCM ice" mask showing the mask from RACMO or from MAR (also in the following figures)?

Figure edited to include runoff time series and scatter plot in other panels. RCM mask is now the same for RACMO and MAR.

Figure 8: Use "Fig." or "figure" consistently.

Done.

Figure 10: Change "Only 2017 shown" to "Only 2017 is shown"

Text changed.

Figure 11: Again, I would remove error bars to increase readability.

Done.

Figure 13: Change "Uncertainty only shown for total MAR runoff, not ice or land components." to "Uncertainties are only shown for MAR total runoff and not the individual land/ice components."

Figure removed. Simplified figures now show total runoff, not separating land and ice.

Figure 15: This plot is very hard to read. Again, I would remove the error bars. It also difficult to distinguish MAR from RACMO. Additionally, "MAR" should be removed from the y-axis labelling.

Figures changed.

2.3.4 Supplementary Material

Figure B1: Remove "not zoomed in". Additionally, I would always provide all necessary information in the figure caption about the comparison (experiment setting, margin/coastal outlet). References to other figures implies constant switching between figures. This also applies for the following figures.

This appendix and these figures have been removed and incorporated into a single figure in the main text.

However, we've gone in the opposite direction regarding figure captions, and they are now even briefer and send the reader elsewhere - not to another figure, but to a section of the text. We know this is not ideal but really don't know how else to handle the current situation. There are 10 figures that are nearly identical, all with six panels. Repeating information for each figure seems unnecessary, and given the height of the figures, there may not even be space. Each figure caption would be 10s of lines. We hope you are OK with the modified figure captions referring readers the Methods section where we introduce the six-panel layout in full detail.

2.4 Review of provided dataset

The presented dataset provides, to my knowledge, a unique and new source for high-resolution discharge data for the GrIS and the unglaciated part of Greenland for the present-day climate (1979 – 2017). The dataset seems very useful for downstream application in various field like e.g. hydrology, ecology and oceanography (particularly for fjord systems). The dataset can be accessed via the provided link, is complete and sufficiently supported with metadata and seems to be of good quality.

However, the description of certain processing steps is insufficient in my opinion and should be improved in the manuscript (see point 2 under "Major comments").

We're happy to hear you think the data set is important and well-produced. The manuscript has been improved with your help and we hope it is now a better document in support of the data.

2.5 Minor Issues

I was not able to found units for the Qaanaaq discharge dataset (https://promice.org/PromiceDataPortal/api/download/0f9dc69b-2e3c-43a2-a928- 36fbb88d7433/version_01/mel)

https://doi.org/10.22008/hokkaido/data/meltwater_discharge/qaanaaq works for me now. I'm not sure what the issue was with the URL you used. Regardless, that DOI remains but GEUS has updated things are we are now using more formal software (the Harvard Dataverse) to server our data.

When checking the static data (basin polygons, outlet locations and streams), I found some inland outlet locations near Kangerlussuaq. What is the reason for this?

This was due to a mask issue and exporting an incorrect variable. It has been fixed.

3 Review 2

This study provides high-resolution datasets of Greenland hydrologic outlets, basins, and streams, and a 1979 through 2017 time series of Greenland liquid water runoff for each outlet. This is a timely and important contribution for the Greenland hydrology community and I'm happy to see the paper and the associated datasets to be published. That said, I think some important issues need to be solved before it can be considered for publishing in ESSD.

Timely and important are nice to hear. Your review was helpful and because of it the paper is now improved.

3.1 General Comments

1/ The result section does not highlight the main contribution of this study very well. It includes numerous numbers of basins, outlets, streams, runoff but their importance is not well demonstrated. Furthermore, this section focuses on the total ice and land runoffs which can be easily derived from RCMs and have been well reported in previous studies. I suggest the result section should focus on what we can learn from runoff partitions in different basins, which is the new contribution of this study.

Following your suggestion we have removed the annual and Greenland-wide comparison (we replace it with a monthly and Disko-only, highlighting the improvements in this work relative to Bamber et al. (2018). We have removed the results section at the suggestion of Reviewer 1 and now have a "Product description" section that highlights this new product.

2/ The discussion section is too long and not easy to follow, particularly "6.2 Validation against observations". Most parts of section 6.2 should be removed to the result section. I suggest the authors only highlight the most important implications of their datasets and shorten this section.

This section has been moved and rewritten, but it is not shorter. The previous Results section was 7 pages of text (3 validation, 4 uncertainty). It is now 11.5 pages (6 validation, 4.5 uncertainty, 1 summary). Importantly, we think the new layout may make it more efficient to read - the contents are more clearly broken down by section and if a reader wants to skip the detailed comparison between modeled discharge and observed discharge (after reading one or two and seeing the pattern), they can more easily do so.

3/ It is important to mention that moulins are not identified so stream networks are delineated to continuously flow from inland to ice edge outlets. Therefore, the stream product may not represent the actual hydrological environments where moulins are widely distributed and fragment drainage networks, such as southwest GrIS. In contrast, the stream product may reasonably predict northwest GrIS drainage pattern since no moulins form there. Moreover, the contributing area threshold should be better illustrated since it determines the extent of streams. It may be useful to state that the derived stream product aims to represent the general meltwater flow pattern rather than the actual spatial distribution of supraglacial rivers and streams.

We now route subglacially, meaning water is assumed to immediately enter the subglacial system. Neglecting some surface flow (likely just a few km citetp:yang_2016_internally) is not likely to impact results because results are reported at the outlet. We also clarify that subglacial streams are model creations and do not represent real streams, although land streams appear to match streams seen in satellite imagery.

4/ The quality of the main figures should be improved. Currently they are not satisfactory for publishing.

Done.

Also, the main point of each figure should be highlighted.

We now refer readers to the section of the text where each figure is discussed. Please see detailed reply to Reviewer 1 about our figure captions, but briefly, given six panels it is not easy to briefly discuss one main point per figure, and often there isn't a specific point. The goal is to introduce data set users to the data, but given the diverse range of possible downstream users, it is difficult to know exactly what their use-case may be and therefore what their focus will be when trying to understand how the modeled discharge compares with observed. Furthermore, with six panels, figure captions will become lengthy, and with the figure repeating 10x, captions would be repetitive. We hope the current choice to limit figure captions and refer readers to the relevant text sections is acceptable.

5/ More previous similar studies should be included. In the paper, the authors only compare their results with Lewis and Smith (2009). However, at least two important similar studies, Andersen et al (2015) and Pitcher et al (2016), should be added as comparison results.

We spent some time searching for papers by Anderson in year 2015 (and other years), that mention Greenland. If you are referring to Andersen et al. (2015), we disagree that is a related paper. That paper (from a colleague at GEUS) addresses the multi-year mean surface mass balance to correct solid ice flux through "gates" at the PROMICE flight line at ~1700 m elevation. It is not about liquid water runoff, or anything at the daily resolution, or hydrologic basins.

Pitcher et al. (2016) is appropriate to cite and we thank the reviewer for reminding us about this paper. We now compare to it in the manuscript, but we are not sure it is "similar". It does address the uncertainty from the k value, which we find to be less uncertain than the uncertainty introduced by multiple RCMs or observations. Beyond that, we do not see any other similarities - Pitcher et al. (2016) focus on one basin, do not provide any geospatial data, any time series of runoff, nor their code.

3.2 Minor Comments

P1 L17, in this paragraph, I think it is necessary to say surface runoff contributes very importantly to Greenland mass balance (along with ice discharge).

Done.

P2 L4, it is not straightforward to understand "liquid runoff form surface melt, condensation, and rainfall".

I'm not sure how to clarify this. We changed it to "liquid runoff from melted ice, rain, and condensation"

P2 L22, why is 100 m ArcticDEM used to do the analysis?

Elsewhere we clarify that when using the 150 m ArcticDEM, streams flow into the wrong fjord. ArcticDEM 100 m had no such artefacts. We did not see the need to use higher resolution ArcticDEM products.

P3 L5, it may be worthy to mention that weathering crust of bare ice layer can store meltwater. Citation is required for this sentence.

We leave this sentence as is. Many things can store water (tundra, cryoconite holes, crevasses etc.) but here we are not listing where storage could occur in reality, only pointing what level of storage are provided by the MAR and RACMO models.

P3 L7, citation is required for this sentence.

Reference added.

P3 L10, it is not common to use the term "hydrologic head elevation".

Changed to "subglacial pressure head", which we do see used in other literature (e.g. Gulley et al. (2014)).

P3 L11, it is unclear how outlets are determined.

Sentence removed. Outlets are provided by the 3rd party GIS tools we used for the routing.

P3 L13, it is unclear what "major streams" means, some specific channel initiation thresholds (i.e. contributing area thresholds) are used to extract streams? It may be useful to call these "major streams" as rivers.

Text has been clarified - we now add "above an upstream contributing area threshold", but keep the word "stream" throughout the document.

P3 L17, why is 1 km2 used as threshold to merge small basins?

It seemed an appropriate balance between too many micro-basins and generating too many unrealistic basins by combining larger basins that should be hydrologically distinct.

P3 L20, "When this value is negative, it indicates submarine (subglacial) discharge", this sentence is not clear.

Sentence has been removed.

P3 L21, this section is too long. I suggest it should be shorten or some parts can be put into SUPP.

We have shortened the section as per your suggestion.

P4 L24, see my general comment, more explanations should be provided for the stream product.

Done.

P5 L8, it is not easy to understand what these numbers mean and why they are important

Paragraph removed.

P5 L15, what does "adjusts" mean here?

This paragraph has been rewritten.

P5 L21, 4380 m3 rather than 4380 m-3.

Paragraph removed.

P5 L23, which basin? also report the similar value in Lewis and Smith (2009).

Paragraph removed.

P5 L26, Mt. Pinatubo eruption, add a citation to support this result.

Paragraph removed.

P5 L27, the land runoff is considerably large. It is useful to further illustrate its meaning.

Paragraph removed.

P6 L7, "Routing with a 5 km DEM is likely to cause some basins and outlets to drain into an incorrect fjord", what is the reason for this?

Changed to "Routing with a 5 km DEM that does not capture small-scale topography". A lower resolution DEM may miss a hill or small mountain range that changes modeled stream patterns.

Fig 2 is not easy to understand. What is the main point of this figure? Perhaps remove it to the SUPP?

It was a graphical depiction of the coverage issues. Removed.

Fig 4, it is not clear why runoff from the Watson River basin plus the two large basins immediately to the south performs better.

This section has been re-written. The reason is likely that the true basin includes the two large basins to the south - that is what is contributes to the observed runoff, so that is what should be included in the model.

Insets are required to show the location of Fig 5 -9 in Greenland.

These figures have been changed but do not include an inset. We invite the reader to refer to Figure 1 for location.

Fig 6 is not easy to follow. What is the meaning to change outlet locations?

The figure has been changed (and is now Figure 2) and the text describing the methods has been clarified and made more central. It is now in the methods section, not in the supplemental material.

Fig 7 is not easy to follow. What is the main point of this figure?

Changed, but still included, and now repeated for each of the observation locations. These figures (now panel a for each location) provide an overview of the observational field site and environment, the basins (land and ice) and the RCM coverage.

Merge Figure B1-B8 into one figure.

Done (now Figure 2).

4 References

Andersen, M. L., L. Stenseng, H. Skourup, W. Colgan, S. A. Khan, S. S. Kristensen, S. B. Andersen, J. E. Box, A. P. Ahlstrøm, X. Fettweis, and R. Forsberg (2015). "Basin-scale partitioning of Greenland ice sheet mass balance components (2007 – 2011)". *Earth and Planetary Science Letters*. 409, 89–95. DOI: 10.1016/j.epsl.2014.10.015.

Bamber, J. L., R. M. Westaway, B. Marzeion, and B. Wouters (2018). "The land ice contribution to sea level during the satellite era". *Environmental Research Letters*. 13 (6), 063008. ISSN: 1748-9326. DOI: 10.1088/1748-9326/aac2f0.

Citterio, M. and A. P. Ahlstrøm (2013). "Brief communication "The aerophotogrammetric map of Greenland ice masses"". *The Cryosphere*. 7 (2), 445–449. ISSN: 1994-0424. DOI: 10.5194/tc-7-445-2013.

Gulley, J. D., P. D. Spellman, M. D. Covington, J. B. Martin, D. I. Benn, and G. A. Catania (2014). "Large values of hydraulic roughness in subglacial conduits during conduit enlargement: Implications for modeling conduit evolution". *Earth Surface Processes and Landforms*. 39 (3), 296–310. DOI: 10.1002/esp.3447.

Lindbäck, K., R. Pettersson, S. H. Doyle, C. Helanow, P. Jansson, S. S. Kristensen, L. Stenseng, R. Forsberg, and A. L. Hubbard (2014). "High-resolution ice thickness and bed topography of a land-terminating section of the Greenland Ice Sheet". *Earth System Science Data*. 6 (2), 331–338. ISSN: 1866-3516. DOI: 10.5194/essd-6-331-2014.

Lindbäck, K., R. Pettersson, A. L. Hubbard, S. H. Doyle, D. van As, A. B. Mikkelsen, and A. A. Fitzpatrick (2015). "Subglacial water drainage, storage, and piracy beneath the Greenland Ice Sheet". *Geophysical Research Letters*. DOI: 10.1002/2015GL065393.

Pitcher, L. H., L. C. Smith, C. J. Gleason, and K. Yang (2016). "CryoSheds: a GIS modeling framework for delineating land-ice watersheds for the Greenland Ice Sheet". *GIScience & Remote Sensing*. 53 (6), 707–722. ISSN: 1943-7226. DOI: 10.1080/15481603.2016.1230084.

Greenland liquid water ~~runoff~~ discharge from ~~1979~~ 1958 through ~~2017~~2019

Kenneth D. Mankoff[1], Brice Noël[5], Xavier Fettweis[2], Andreas P. Ahlstrøm[1], William Colgan[1], Ken Kondo[3], Kirsty Langley[4], Shin Sugiyama[3], Dirk van As[1], and Robert S. Fausto[1]

[1]Department of Glaciology and Climate, Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark
[2]Department of Geography, University of Liège, Belgium
[3]Institute of Low Temperature Science, Hokkaido University, Japan
[4]Asiaq-Greenland Survey, Nuuk, Greenland
[5]Institute for Marine and Atmospheric Research, Utrecht University, The Netherlands

Correspondence: Ken Mankoff (kdm@geus.dk)

Abstract. ~~We provide high-resolution datasets of~~ Greenland runoff, from ice mass loss and increasing rainfall, is increasing. That runoff then discharges and impacts the physical, chemical, and biological properties of the adjacent fjords. However, where and when the discharge occurs is not readily available in an open database. Here we provide datasets of high-resolution Greenland hydrologic outlets, basins, and streams, and a ~~1979 through 2017~~ daily 1958 through 2019 time series of Greenland liquid water ~~runoff~~ discharge for each outlet. ~~Outlets,~~ The data include 24507 ice marginal outlets and upstream basins, and ~~streams are derived from traditional hydrologic routing algorithms over the surface of a~~ 29635 land coast outlets and upstream basins, derived from the 100 m ArcticDEM ~~digital elevation model (DEM) twice: Once to the ice margin and once to the coast. We then partition liquid water runoff from both ice~~ and ~~land~~ 150 m BedMachine. At each outlet there are daily discharge data for 22644 days - ice sheet runoff routed subglacially to ice margin outlets, and land runoff routed to coast outlets - from two regional climate models (RCMs; MAR and RACMO)~~into each basin and at each outlet location. The data include 18903 ice basins and outlets (614 basins greater than 10 km²), 30241 land basins and outlets (958 basins greater than 10 km²), major streams in each basin, and daily runoff water volume flow rate at each outlet from each of two RCMs. We perform a~~ . Our sensitivity study of ~~outlet location change for every ice sheet location over a range of hydrologic routing assumptionsand data sets. Annual runoff from the ice ranges from ~136 km³ in 1992 to ~785 km³ in 2012. Daily maximum ice runoff from one basin is as large as 4380 m³ s⁻¹. Both ice runoff magnitude and variability increase over the time series. Land runoff contributes an additional ~35 % to the ice runoff. Comparison with 9 basins instrumented with stream gauges shows a range of (dis)agreement from poor to excellent between our estimated dischargeand observations. As part of the journal's living archive option, and our goal to make an operational product, all input data, code, and results~~ how outlet location changes for every inland cell based on subglacial routing assumptions, shows that most inland cells where runoff occurs are not highly sensitive to those routing assumptions, and outflow location does not move far. We compare RCM results with 10 streams instrumented with gauges spanning four orders of magnitude of daily discharge. Results show that for daily discharge at individual basin scale the 95 % prediction interval generally falls within plus-or-minus a factor of five (half an order of magnitude, or +500%/-80%). Results from this study ~~will be updated as needed (when new input data are available , as new features are added, or to~~

fix bugs) and made available at are available at doi:10.22008/promice/freshwater (Mankoff, 2020a) and code is available at http://github.com/mankoff/freshwater (Mankoff, 2020b).

1 Introduction

1 Introduction

Over the past decades, liquid runoff from Greenland has increased (Mernild and Liston, 2012; Bamber et al., 2018; Trusel et al., 2018; Perner et al., 2019) contributing to mass decrease (Sasgen et al., 2020). When that runoff leaves the ice sheet and enters discharges into fjords and coastal seas, it influences a wide range of physical (Straneo et al., 2011; An et al., 2012; Mortensen et al., 2013; Bendtsen et al., 2015; Cowton et al., 2015; Mankoff et al., 2016; Fried et al., 2019; Cowton et al., 2019; Beckmann et al., 2019), chemical (Kanna et al., 2018; Balmonte et al., 2019), and biological (Kamenos et al., 2012; Kanna et al., 2018; Balmonte et al., 2019) systems (Catania et al., 2019). The scale of impacts ranges from scales of the impacts range from instantaneous at the ice-ocean boundary to the distal open decadal in the distal ocean (Gillard et al., 2016). The influence of freshwater on multiple domains and disciplines (Catania et al., 2019) is the reason several past studies have estimated runoff and discharge at various temporal and spatial scales (e.g. Mernild et al. (2008, 2009, 2010a); Mernild et al. (2015); Mernild et al. (2017); Merni

To date no product provides discharge estimates at stream spatial resolution (~100 m), daily temporal resolution, for all of Greenland, covering a broad time span (1958 through 2019), from multiple regional climate models (RCMs), and with a simple database access software to support downstream users. Here we present these data. In the following description and methods, we document the inputs, assumptions, methodologies, and results we use to estimate Greenland discharge from 1958 through 2019. This product is available at doi:10.22008/promice/freshwater (Mankoff, 2020a).

Freshwater discharge from Greenland primarily takes three forms: solid ice from calving at marine terminating glaciers, submarine meltwater from ice-ocean boundary melting at marine terminating glaciers, and liquid runoff from surface melt, condensation, and rainfall. Immediately upstream from the grounding line, no submarine melting has occurred and that water is still solid icemelted inland surface ice, rain, and condensation. A recent paper by **?** targets the solid ice discharge plus submarine melt budget by estimating solid ice discharge across flux the ice flow rate across gates 5 km upstream from all fast-flowing marine terminating glaciers in Greenland. Complementing that paper, this paper targets Greenland's point-source liquid water runoff discharge budget by partitioning RCM runoff estimates to all ice margin and coastal outlets. The sum of this data product and these data and **?** is an estimate of the majority of freshwater (in both liquid and solid iceform) volume flow rates into Greenland fjords. Those two terms comprise the bulk but not all of freshwater volume freshwater - they exclude relatively minor contributions from precipitation directly onto the fjord surface, or ocean surface, and relatively minor contributions from evaporation and condensation, sea ice formation and melt, or subglacial basal melting. Much work remains to determine which portion of solid ice across a flux gate becomes submarine melt, and where and when the solid ice, i.e. icebergs, melts in the fjord.

In this data set description we present a Greenland wide product of liquid water runoff time series and a high-resolution map of hydrologic outlets, basins, and streams. The daily runoff water volume flow rate for the period of 1979 through 2017 are based on runoff from land or ice estimated by two regional climate models (RCMs) and has a 100 m spatial resolution including outlets, basins, and streams (at the ice margin and coast). In the following description and methods, we document the inputs, assumptions, methodologies, and results we use to estimate Greenland runoff from 1979 through 2017. This product is available at .

2 Input Dataand validation data

2.1 Static data

The static products (streams, outlets, and basins (Fig. 1)) are derived from an ice-sheet surface DEMdigital elevation model (DEM), an ice-sheet mask, the land surface DEM, and an ocean mask. For the surface DEM, we use the ArcticDEM v7 100 m product (Porter et al., 2018). When using subglacial routing , we use Subglacial routing uses ArcticDEM and ice thickness from BedMachine v3 (Morlighem et al., 2017a, b). For the ice mask we use the Programme for Monitoring of the Greenland Ice Sheet (PROMICE) Ice Extent (Citterio and Ahlstrøm, 2013). For the ocean mask we use the Making Earth System Data Records for Use in Research Environments (MEaSUREs) Greenland Ice Mapping Project (GIMP) Land Ice and Ocean Classification Mask, Version 1 (Howat, 2017b; Howat et al., 2014). Satellite basemap imagery comes from , specifically the National Snow and Ice Data Center (NSIDC) MEaSUREs GIMP data set with ID 0713 .

2.2 RCM time series

The time series product (daily runoffdischarge) is derived from gridded daily runoff estimates from RCM calculations over the land and ice areas of Greenland. The daily runoff comes from We use the Modèle Atmosphérique Régional (MAR; Fettweis et al. (2017), 15 km resolution) and the Regional Atmospheric Climate Model (RACMO; Noël et al. (2019), 5.5 km resolution)and runoff). Runoff, R, is defined by

$$R = ME + RA - RT - RF. \quad (1)$$

where In Eq. 1, ME is melt, RA is rainfall, RT is retention, and RF is refreezing. In RACMO, retention occurs only when there is firn , firn is present (not with bare ice, while MAR has a runoff). MAR does have a delay for bare ice runoff, but not . Neither have a delay for land runoff. Both RCM results were provided regridded to a the same 1 km resolution grid using an offline statistical down-scaling technique based on local vertical runoff gradient applied to the sub-grid topography . MAR simulations were run using version 3.9.6 . RACMO simulations were run using version (Noël et al., 2016; Fettweis et al., 2020). MAR (v 3.11; Delhasse et al. (2019)) ran with 7.5 km resolution and ERA 6-hour forcing. RACMO (v 2.3p2. Both RCMs use ; Noël et al. (2018)) ran with 5.5 km resolution and ERA-Interim 6-hour forcing. Runoff is assigned an uncertainty of ± 15 %.

2.3 River discharge observations

We use 10 river discharge daily time series to validate the results of this work. The name, location, time coverage, and relevant data and scientific publications associated with each of these observational data are listed in Table 1.

Table 1. Table of observation locations, time spans, and associated references. Coordinates are decimal degree W and N.

Location	Lon	Lat	Time	Data	Publication	Fig(s).
Kiattuut Sermiat	45.33	61.21	2013	Hawkings et al. (2016a)	Hawkings et al. (2016b)	1 4 5 6 10
Kingigtorssuaq (Nuuk)	51.5801	64.1387	2008-2018	Langley (2020)		1 4 5 11
Kobbefjord (Nuuk)	51.3810	64.1336	2006-2017	Langley (2020)		1 4 5 14
Leverett Glacier	50.17	67.06	2009-2012	Tedstone et al. (2017)	Hawkings et al. (2015)	1 4 5 6 9
Oriartorfik (Nuuk)	51.4066	64.1707	2007-2018	Langley (2020)		1 4 5 12
Qaanaaq	69.3030	77.4753	2017-2018	Kondo and Sugiyama (2020)	Sugiyama et al. (2014)	1 4 5 6 17
Røde Elv (Disko)	53.4989	69.2534	2017	Langley (2020)		1 6 4 5 6 15
Teqinngalip (Nuuk)	51.5484	64.1586	2007-2018	Langley (2020)		1 4 5 13
Watson River	50.68	67.01	2006-2019	van As et al. (2018)	van As et al. (2018)	1 4 5 6 7 8
Zackenberg	20.5628	74.4722	1996-2018	Langley (2020)		1 4 5 6 16

3 Methods

3.1 Terminology

We use the following terminology throughout the document:

- Runoff refers to the unmodified RCM data products - melted ice, rain, condensation, and other RCM outputs that are inputs to this work.
- Discharge refers to the runoff after it has been processed by this work - routed to and aggregated at the outlets. Depending on context, discharge may also refer to the observed stream discharge (Table 1).
- Basins refer to the 100 m x 100 m resolution basins derived from a combination of the ArcticDEM product and the mask.
- Mask refers to the surface classification at that 100 m x 100 m resolution and is one of ice, land, or ocean (also called fjord or water). When referring to the surface classification in the RCM, we explicitly state "RCM mask".
- MAR and RACMO refer to the RCMs, but when comparing discharge estimates between them or to observations, we use MAR and RACMO to refer to our discharge product derived from the MAR and RACMO RCM runoff variables,

rather than repeatedly explicitly stating "discharged derived from [MAR|RACMO] runoff". The use should be clear from context.

- The ±95 % quantile range refers to data < 95 %, or > 5 %, and is therefore only 90 % of the data.

3.2 Streams, outlets, and basins

Streams are calculated from the ~~hydrologic head elevation, that~~ hydraulic head h which is the DEM surface for land surface routing, or the subglacial pressure head elevation for subglacial routing~~(only performed as part of the uncertainty estimate)~~. ~~Outlets are defined as~~ h is defined as

$$h = z_b + k\frac{\rho_i}{\rho_w}(z_s - z_b), \tag{2}$$

with z_b the ice-free land surface and basal topography, k the flotation fraction, ρ_i the density of ice (917 kg m^{-3}), ρ_w the density of water (1000 kg m^{-3}), and z_s the land surface for both ice free and ice covered surfaces.

Eq. 2 comes from Shreve (1972) where the hydropotential has units Pa, but here is divided by gravitational acceleration g times the density of water ρ_w to convert the units from Pa to m. We compute h and from that streams, outlets, basins, and runoff for a range of subglacial pressures, implemented as a range of k values: 0.8, 0.9, and 1.0. We use these three scenarios to estimate sensitivity of the outlet location for all upstream cells, but otherwise only use results from the $k = 1.0$ scenario. Eq. 2 makes the assumption that when ice is present all water routes subglacially, meaning that water flows from the surface to the bed in the grid cell ~~location where streams terminate at the ice margin or coastal boundary. Each outlet has one upstream basin and each basin has one outlet . Only major streams are defined, so small basins may have outlets but no streams~~where it is generated. In reality, internal catchments and moulins likely drain waters to the bed within a few km of their source (Yang and Smith, 2016). The difference between some supraglacial flow and immediate subglacial flow is not likely to impact results because discharge is reported only at the outlet locations.

We use the GRASS GIS software ~~package~~ (Neteler et al., 2012; GRASS Development Team, 2018) and the `r.stream.extract` ~~tool configured for multi-flow~~ command configured for single-flow direction from eight neighbors (~~MFD-8~~SFD-8) to calculate ~~the primary flow direction~~ streams and outlets at the ice edge and coast~~, and then~~. Streams are defined only if their upstream contributing area is above a threshold, so small basins may have outlets but no streams. The software fills all sinks so that all water flows to the domain edge. We then use the `r.stream.basins` tool (Jasiewicz and Metz, 2011) to calculate basins ~~and streams~~ upstream from each outlet. Basins < 1 km^2 are absorbed into their largest neighbor and the associated outlets are dropped.

~~Finally, for both domains (land and ice) we calculate zonal statistics for each basin and day for the RCM ice and land runoff. Outlet metadata data includes the BedMachine elevation at the outlet location. When this value is negative, it indicates submarine (subglacial) discharge~~

3.2.1 Outlet sensitivity

The three choices of k generate three scenarios of basins and outlets, and we use this to show sensitivity of every ice grid cell to these choices. After three k-scenarios, each cell has three possible outlets, where each outlet is an (x,y) coordinate. To show results in a map view, we reduced these six properties (three 2D coordinates) to a single property. For every grid cell in the ice domain we compute the distance between each outlet and the other two (six becomes three), and then select the maximum (three becomes one). Fig. 2 displays the maximum distance - a worst-case scenario - of how far the outlet of every inland ice cell may move due to basal routing assumptions.

3.3 Discharge and RCM coverage

RCM runoff is summed over each basin for each day of RCM data, and assigned to each outlet for that day. This assumes routing between the runoff and the outlet is instantaneous, so all analyses done here include a seven-day smooth applied as in van As et al. (2017). The released data do not include any smoothing.

3.4 ~~Coverage~~

The alignment of the RCM and the basins do not always agree. Each 100 m ~~2~~ x 100 m ArcticDEM pixel is classified as ice ~~, land, or fjord~~(Citterio and Ahlstrøm, 2013), ocean (Howat, 2017b), or land (defined as neither ice nor ocean). However, the ~~ice boundary , the coast boundary ,~~ classification of the mask cells and the 1 km^2 ~~statistically-downscaled~~ RCM domains do not always agree ~~with each other on the classification of a given grid cell. A disagreement occurs,~~ - for example, when a ~~basin~~ mask cell is classified as ~~glacier in Citterio and Ahlstrøm (2013)~~ ice but the matching RCM cell is land~~, or vice versa~~. This disagreement occurs almost everywhere along the ice margin because the 1 km resolution RCM boundary and the 100 m mask boundary rarely perfectly align. ~~It also occurs wherever nunatuks exist, because ice-sheet interior "holes" are filled, otherwise they falsely act as interior drains.~~ The ice margin is ~~also where the majority of~~ where most runoff occurs due to the highest temperatures at the lowest ice elevations~~. Small~~ , so small changes in masks in these locations can introduce large changes in RCM outputs.

We adjust for this imprecise overlap and scale the RCM results to the basin ~~using the following method (Fig. ??)~~area. Where the ~~surface~~ mask reports ice and a RCM reports land, the RCM land runoff fraction is discarded~~(this reduces annual average runoff by ~5 %)~~, and the RCM ice runoff fraction over this basin is ~~used to compensate~~ adjusted for the uncovered basin cells ~~. For example, if an ice basin is only 90 % covered by ice in an RCM, the runoff is divided by 0.9 to estimate total runoff. Where a basin reports land and the RCM reports ice, the same method as above is applied, but for land. When a small basin has no RCM cells~~ (and vice versa for basin land and RCM ice). Small basins with no RCM coverage of the same ~~classification covering any part of it, that basin never has any reported runoff. This method means that RCM runoffis not conserved through this work - RCM inputs to our algorithm do not equal our reported output which are ~3 % higher on an annual average~~type have no runoff.

Runoff adjustments using this method are underestimated for large basins with large inland high elevation regions with low runoff, because this method fills in misaligned cells with each days average ~~runoff~~discharge, but the misalignment (missing runoff) occurs at the ice sheet edge where maximum runoff occurs. However, given that the basin is large, misalignment is proportionally small, and therefore errors are proportionally small. When misalignment is proportionally large (e.g. a basin is only ~~~~~1 % covered by the same RCM classification), that implies a small basin ~~. In the case of a small basin, the covered part must be~~ with the covered region near the uncovered ~~part, the infilling~~ region, and the filling method therefore uses ~~spatially~~ nearby data, and ~~there is no underestimate.~~

~~At the basin scale, fractional coverage ranges from 0 to 1. Coverage equal to 0 occurs where a basin does not have a MAR or RACMO cell of the same type (ice or land) over any part of it. Coverage close to 0 occurs where a basin has one grid cell (100 m^2) overlapped by a MAR or RACMO cell of the same type, but the rest of the basin has no overlap. Coverage equal to 1 occurs where a basin is completely overlapped by MAR or RACMO cells of the same type~~not distal high-elevation data, and there should not be a large underestimate.

RCM inputs are also scaled by the projection area error between the EPSG:3413 map projection of the RCM and an approximation of the true earth spheroid. This error is up to 8 % for some grid cells, but ranges from - 6 % to + 8 % over Greenland and the cumulative error for the entire ice sheet is < 8 %.

4 ~~Product Description~~

3.1 Validation

We validate the modeled outlet discharge against the observations first in bulk and then individually. Bulk comparisons are done with scatter plots (Figs. 3 & 4), and modified Tukey plots comparing observations vs. differences (Fig. 5, based on Tukey mean-difference plots, also known as Bland-Altman plots (Altman and Bland, 1983; Martin Bland and Altman, 1986)). When comparing modeled with observed discharge, we drop any days where observed discharge is zero or modeled discharge is less than 1 m^3 day^{-1} .

~~This liquid water runoff product for Greenland contains a static map of Greenland's hydrological outlets, basins, and streams and a times-series of runoff from each outlet~~We introduce the graphics here as part of the methods to reduce replication in figure captions - we show 10 nearly identical graphics (Figs. 7 and 9 through 17) for 10 different observation locations, and each graphic uses the same template of six panels.

~~The output data is provided in the following formats: The stream product is provided as aGeoPackage standard GIS product and a metadata CSV that includes the stream type (start or intermediate segment) , network, stream along-flow length, stream straight length, sinuosity, source elevation, outlet elevation, and a variety of stream indices such as the Strahler, Horton, Shreve, Hack, and other parameters . The outlet product is also provided as a GeoPackage and CSV, each of which include the outlet ID (linked to the basin ID), the longitude, latitude, EPSG:3413 x and y~~For each figure (Figs. 7, 9 to 17), the top panel (a) shows a satellite basemap with the land portion of the basin of interest (if it exists) outlined in dark green, the streams within that basin in light green, the basin outlet as an orange filled diamond, and the stream gauge location as an orange unfilled diamond. Ice basin(s) that drain to the outlet are outlined in thick dark blue if they exist, and all other ice basins in thin dark blue. The RCM ice domain is in light blue, and RCM land domain not shown, but is outside the light blue ice domain (not including the water). The scale of each map varies, but the basins lines (green and dark blue) are discretized at 100 m resolution, and the ~~outlet elevation. The basin product GeoPackage includes the geospatial region that defines the basin. The metadata CSV includes the basin ID (linked to the outlet ID), and the area of each basin. The time-series discharge product is provided as annual NetCDF files, four per year, one for each domain (ice margin, land coast) and one for each RCM (MAR and RACMO~~RCM grid cells (light blue) are at 1 km resolution.

Panel b shows an example time series - whatever data are available for the last calendar year of the observations.

Panel c shows a scatter plot of observations vs. RCM-derived discharge. This is the same data shown in Fig. 3, but subset to just the basin of interest. Color encodes day-of-year, and a kernel density estimation (KDE) of the discharge values highlights where most points occur - not necessarily visible without the KDE because the points overlap (total number of plotted points is printed on the graphic near "n:"). The r^2 correlation coefficient for each RCM-derived discharge is displayed. The gray band shows the 95 % prediction interval, and the three solid lines mark the 1:1, 1:5, and 5:1 ratios.

Panel d shows observations vs. difference. This is the same data shown in Fig. 5, but subset to just the basin of interest. Color denotes sample density (similar to the KDE in panel c). The ~~NetCDF file contains an unlimited time dimension, usually containing 365 or 366 days, much of the same metadata as the outlets CSV file, including the outlet (a.k. a station) ID, the latitude, longitude, and altitude of the outlet~~horizontal lines mark the mean, 0.05, and 0.95 quantile of the scale difference between the RCM and the observations. Scale difference means that a value of 1 (or 10^0) is agreement between observations and the RCM, and a ~~runoff variable with dimensions (station, time) and units m^3 s^{-1}~~value of 2 or 0.5 is a factor of 2 or a +100/-50 % disagreement. The horizontal split marks the bottom 1/3rd and top 2/3rds quantiles of discharge.

4 ~~Results~~Product evaluation and assessment

Results of this work include 1) ice-margin terminating streams, outlets, and basins, 2) coast-terminating streams, outlets, and basins~~(this product is a super-set of (1), and includes the upstream ice streams and basins)~~, 3) ~~runoff~~ discharge at the ice-marginal outlets from ice runoff and 4) ~~runoff~~ discharge at the coastal outlets from land runoff. ~~Runoff ice products are in duplicate from~~ Discharge products are provided from both the MAR and RACMO RCMs.

~~Fig. 1 illustrates 18903 ice basins and outlets and 30241 land basins and outlets. Among these ice basins we find 614 greater than 10 km^2 and 42 greater than 100 km^2, while the land basins have 958 greater than 10 km^2 and 47 greater than 100 km^2~~We note that our subglacial streams represent where the model routes the water, and does not indicate actual streams, unlike the land streams that do appear near actual streams when compared to satellite imagery. Even so, these streams routed using simple subglacial theory show remarkable alignment with ice surface streams and lakes visible in satellite imagery. This may support the theory that basal topography exerts a strong control on supraglacial hydrology (Lampkin and VanderBerg, 2011; Sergienko, 2013; Crozier et al., 2018), or may indicate a poorly represented and smooth bed in BedMachine, and therefore Eq. 2 is effectively applying surface routing in these locations.

~~Overall this amounts to 1,807,264~~ Of the 361,950 km^2 of basin ~~ice cells, of which 1,769,087 km^2 are covered by ice in MAR, 37,669 km^2 are covered by land,~~ land cells, the RCMs cover 339,749 km^2 ($\sim$94 %) with their land grid cells, and ~~479 km^2 are covered by fjord. There are 336,497~~ 22,201 km^2 ($\sim$6 %) of basin grid cells are filled in with our coverage algorithm (Sect. 3.3; the RCMs have these as ice or ocean). Alternatively, 51,532 km^2 of RCM land are discarded because the basins classify part or all of these cells as ice or ocean. Of the 1,781,816 km^2 of basin ~~land cells, of which 306,256 km^2 are covered by land in MAR, 10,569 km^2 are covered by ice,~~ ice cells, the RCMs cover 1,760,912 km^2 ($\sim$99 %) with their ice cells, and ~~19,672 km^2 are covered by fjord. The total Greenland coverage of RACMO is similar~~ 20,904 km^2 ($\sim$1 %) of basin grid cells are filled in (the RCMs have these as land or ocean). Alternatively, 21,793 km^2 of RCM ice are discarded, because the basins classify part or all of these cells as land or ice (Table and data available in Supplemental Online Material).

Our ~~grid cell land classification correction~~ coverage correction (Sect. 3.3) adjusts RCM ice runoff values by $\sim$~~8 %. As mentioned, the misalignment between the ice , land, and ocean masks and the RCM land type~~ 3 %. Discarding RCM ice runoff that does not match the underlying mask ice cells results in a ~~total ice sheet runoff~~ $\sim$5 % ~~less than the RCM runoff inputs when runoff is only accumulated where the RCM ice grid cells align with the basin ice grid cells~~reduction in discharge. However, ~~when~~ applying our coverage algorithm ~~is subsequently applied~~ to adjust RCM inputs for regions where basins have ice but the RCMs do not ~~, total ice sheet runoff is~~ results in an 8 % increase from the reduced discharge (net gain of $\sim$3 %~~more than the RCM inputs~~). A similar adjustment occurs for RCM land runoff.

~~Figure ?? shows the time-series product spanning the period from `1979` through `2017`, containing `14244` days. Daily runoff values range from a minimum of 0 m^3 to a maximum of `4380` m^{-3} on `'2012-08-06'` located on the western part of the ice sheet south of Sermeq Kujalleq (Jakobshavn Isbræ) (50.68 E, 68.31 N, 203 m a.s.l). Annual runoff has a maximum of `18` km^3 from one basin (a similar value as reported by Lewis and Smith (2009)).~~

~~Annual average ice runoff has a 1979 through 2017 mean of $\sim$400 ±30 km^3 (± 15 %), a 1992 minimum of 136 ± 10 km^3 (MAR ice) and 191 ± 14 km^3 (RACMO ice), and a 2012 maximum of 785 ± 59 km^3 (MAR) and 693 ± 50 km^3 (RACMO) (Fig. ??). The 1992 low is likely due to the Mt. Pinatubo eruption, and then 2nd lowest runoff year, 1983, due to El Chichón eruption. The land runoff (MAR only) contributes an additional 35 % to the ice runoff on average, with a range from 18 % (142 ± 10 km^3 during the 2012 high ice-runoff year) to 83 % (112 ± 8 km^3 during the 1992 low ice-runoff year).~~

~~During the first decade of the time series, ice runoff had a mean of 305 ± 23 km^3 (MAR) or 325 ± 24 km^3 (RACMO), ranged from $\sim$200 ± 15 km^3 to $\sim$390 ± 30 km^3, and had an annual standard deviation of 60 km^3. During the last decade of the time series, ice runoff had a mean of 531 ± 38 km^3 (MAR) or 519 ± 38 km^3 (RACMO), ranged from $\sim$370 ± 28 km^3 to 785 ± 59 km^3, and had an annual standard deviation of 130 km^3. From this, it is evident that ice runoff varies widely but increases in both magnitude and variability over the duration of the time-series.~~

5 ~~Discussion~~

4.1 Comparison with previous similar work

Our static products - streams, outlets, and basins - have been previously estimated. Lewis and Smith (2009) identified 293 distinct hydrologic ice basins and provided a data set of ice basins and ice margin outlets. Our work, a decade later, has ~~significantly~~ ~2 orders of magnitude more basins and outlets because of the higher resolution of the input data, and ~~additional data products~~includes additional data. We provide ice basins, ice margin outlets, ice streams with metadata, land basins, coastal outlets, and land streams with metadata. Lewis and Smith (2009) generated basins from a 5 km DEM, compared to the 100 m DEM used here. Routing with a 5 km DEM that does not capture small-scale topography is likely to cause some basins and outlets to drain into an incorrect fjord ~~. When comparing BedMachine v3 (~~ - we find that some land basins delineated with even the 150 m ~~) and ArcticDEM (~~BedMachine land surface may drain into the incorrect fjord, but we did not find similar errors with the 100 ~~m) products, land DEM errors or resolution limitations cause some BedMachine basins to drain on the opposite side of a spit or an isthmus than they appear to in satellite imagery - imagery that is closely matched by the nearby flow-path as routed using ArcticDEM~~ m ArcticDEM product used in this work.

Our time-series product - ~~runoff~~discharge, also has existing similar products. The most recent of these is from Bamber et al. (2018) ~~(Fig. ??)~~ who provide a data product at lower spatial resolution (5 km), lower temporal resolution (monthly), and only coastal discharge, not coastal basins, ~~nor~~ ice basins, ~~nor~~ or ice margin outlets and discharge. However, Bamber et al. (2018) surpasses our product in that ~~the time-series extends back to 1958, and~~ spatial coverage includes a larger portion of the Arctic including Iceland, Svalbard, and Arctic Canada. ~~Futhermore~~Furthermore, by providing data at 5 km spatial and monthly temporal resolution, Bamber et al. (2018) implements the main strategy suggested here to increase the signal-to-noise ratio of the data - averaging discharge in space or time (see Sect. 4.3.5).

4.2 ~~Validation against observations~~

~~There are many regional products that estimate a single or a few basins and associated runoff over a range of spatial resolutions and a range of temporal resolutions and periods. Examples of these include~~ We show both the geospatial and temporal differences between this product and the Bamber et al. (2018) for an example location - Disko Island (Fig. 6). Spatially our product allows assessment of discharge at interior locations, necessary when comparing with observations that are not at the coast (for example, the Leverett Glacier observations (Fig. 9)). Temporally, the MAR and RACMO runoff summed over all of Disko Island and to monthly resolution is similar to the monthly Disko discharge of **?**, but the daily resolution shows increased variability and individual discharge events (from warm days or rain) not seen in the monthly view.

A similar GIS workflow was presented by Pitcher et al. (2016) only focusing on the discharge uncertainty from basal routing assumptions (the k parameter in Eq 2). We find these differences to be smaller than the differences between RCMs or between RCM and observations (see Sect. 4.3).

4.2 Validation against observations

Here we compare our results to all observations that we have been able to findthat are publicly accessiblepublicly accessible observations we could find, or willing to become open and publicly accessible as part of this work (Table 1).

This validation compares discharge derived from RCM runoff estimated far inland on the ice sheet. That runoff is both spatially and temporally disconnected from the stream discharge observations used here. Disagreement is expected and does not indicated any specific issues in the RCMs, but are instead likely due to our routing algorithm (Sect. 3.3). These comparisons include (1)Watson River discharge from van As et al. (2018),

Below we discuss first the validation for all points, then the individual outlets. For the individual outlets we begin by focusing on the "problematic" results in order of severity: Watson River (Figs. 7 & 8), Leverett Glacier (Fig. 9), and Kiattuut Sermiat (Fig. 10), and show that for two of these three, simple solutions are available, although manual intervention is needed to detect the issue and then adjust results.

4.2.1 Bulk validation

A comparison of every day of observational data with discharge > 0 (2)Greenland Ecosystem Monitoring Programme (GEM)data for six basins around Zackenberg, Disko Island, 15,778 days) and the two RCMs (Fig. 3) shows good agreement with r^2 of 0.45 and Nuuk,0.88 for discharge derived from MAR and RACMO runoff respectively (hereafter "MAR" and (3) Runoff from a small basin near Qaanaaq, in Northwest Greenland. "RACMO"). For RACMO this is within a factor of five spanning four orders of magnitude, although both RCMs report only ~50 % of the observed discharge for the largest volumes at the Watson River outlet (Fig. 7). The reason for the disagreement at the Watson River outlet is discussed in detail in Sect. 4.2.2.

4.2.2 Watson River

The four near-Nuuk GEM basins (Table 1, Sect. 4.2.5) have ice basins but either no or limited coverage in the RCMs. When excluding these basins from the comparison the r^2 agreement changes to 0.59 and 0.78 for MAR and RACMO respectively and the 95 % prediction interval is significantly smaller for MAR (red band in Fig. 3). The largest disagreements throughout this work comes from these small basins with no RCM coverage. These disagreements are therefore indicative of differences between the land/ice classification mask used by the RCMs compared with the basin masks used here, not necessarily the ability of the models to simulate melting ice or local weather.

We compare the observed Watson River discharge from van As et al. (2018) to the runoff from the nearest outlet in this work. We note that runoff from this work matches for low runoff (< 500 Fig. 4 shows a similar view as Fig. 3, but here each observational data set and associated daily discharge is summed by year for all and only the days in that year that observations exist (hence units m^3 and not m^3 yr^{-1}; for example the single "Ks" and "R" means is only one calendar year with some observations at the Kiattuut Sermiat and Røde Elv outlets, respectively). Here it is more clear that the Watson River outlet (Sect. 4.2.2) reports ~50 % of the observed discharge, the Kiattuut Sermiat outlet (Sect. 4.2.4) over-estimates discharge, and the remainder fall within the factor-of-two lines, except for low discharge at Kingigtorssuaq in the MAR RCM where the RCMs do not cover that small glacier (Sect. 4.2.5).

Because discharge spans a wide range (~4 orders of magnitude, Fig. 3), a high correlation (r^2 of 0.88, Fig. 3) may be due primarily to the range which is larger than the error (Altman and Bland, 1983; Martin Bland and Altman, 1986). Fig. 5 compensates for this and more clearly shows bias and the range of errors. This graphic again excludes the four near-Nuuk GEM basins. From Fig. 5, the top 2/3rds of observed discharge has modeled discharge under-estimated by a scale of 0.78 (MAR) and 0.73 (RACMO), and ± 95 % quantile of 0.30 to 2.06. The top 2/3rds of discharge spans ~2 orders of magnitude (width of horizontal line, from ~10^1 to ~10^3 m^3 s^{-1}, 93 % of all runoff days), and has a ±95 % quantile uncertainty of ~±0.5 order of magnitude, or half of the range of the data. Put differently, days with high observed discharge may have modeled discharge within ±0.5 order of magnitude, or plus-or-minus a factor of five, or +500/-80 %. The modeled discharge is not likely to move farther than this from the observations, and high discharge remains high.

The bottom third of discharge is where the largest disagreement occurs. The mean model values are near the observed - discharge is scaled by 0.69 for MAR (~31 % low) and 1.08 for RACMO (~8 % high), but is only approximately half of the van As et al. (2018) runoff for high runoff ±95 % quantile range is large. Although large uncertainties for low discharge may not seem to matter for some uses (e.g. estimates of total discharge from Greenland, which is dominated by the largest quantities of discharge), it may matter for other uses. The bottom 1/3 quantile of observed discharge spans 3 orders of magnitude (10^{-2} to ~10^1) but the uncertainty spans ~4 and ~2 orders of magnitude for MAR and RACMO respectively (~10^{-3} to ~2.2×10^1 MAR; ~10^{-1} to 2.2×10^1 RACMO).

4.2.2 Watson River

The Watson River discharge basin are is 1882 km^2, of which 521 km^2 (28 %) are land and 1361 km^2 (72 %) are ice (Fig 7a). The partial (last calendar year) discharge time series shows MAR and RACMO agree well with each other, but have a maximum of 500 m^3 s^{-1} while observations are up to 4x more (Fig. 7b). Low discharge (both early and late season) is over-estimated and high discharge is under-estimated, approximately equal for both RCMs (Fig. ??). This difference 7c). The low discharge over-estimate ranges from a mean multiple of 1.64 (MAR) and 1.55 (RACMO) to a +95 % quantile scale ~70 (MAR) and ~50 (RACMO). The high-discharge under-estimate has a mean multiple of 0.5 for both MAR and RACMO, and a ±95 quantile range of between 0.23 to 1.06.

The Watson River discharge presented here is approximately half of the van As et al. (2018) discharge for high discharge. The large underestimate for high discharge may be due to either errors in the basin delineation used in this study, errors in the stage-discharge relationship used by van As et al. (2018), errors in the RCM runoff estimates, or a combination of the above three. All three of these error sources increase with high melt or runoff; discharge (and associated melt): Basin delineation becomes less certain with inland distance from the ice sheet margin. The river stage-discharge conversion becomes less certain at high stage levels. Runoff calculations become less certain from a snow surface are more uncertain than from than an ice surface, because of e.g. snow density, subsurface refreezing, and surface darkening.

The complexity of estimating the area of the Watson River catchment is described by Monteban et al. (2020), who note that previous studies have used values ranging from 6131 km^2 (Mernild et al., 2010b) to 12547 km^2 van As et al. (2012). Our basin is smaller than the basin used in van As et al. (2018) and similar to Mernild et al. (2018) who attributed the difference between their modeled outflow and observations from van As et al. (2017) to their decision to use surface rather than subglacial routing, and applied a correction term. We find that our basin does not include ice a separate basin here to the south of itself that is included in van As et al. (2018). When we manually add the two large ice basins to the south that is part of the Watson River basin, runoff estimates agree (Fig. ?? right panel), suggesting basin delineation, not stage-discharge or RCM may be the primary cause for this disagreementice basin in van As et al. (2018) (from Lindbäck et al. (2015) and Lindbäck et al. (2014)). We are able to recreate the van As et al. (2018) basin (introduced in Lindbäck et al. (2015)) but only when using the Lindbäck et al. (2014) bed and the Bamber et al. (2013) surface. When using only one or zero of those and any combination of BedMachine v2 (Morlighem et al., 2014), BedMachine v3, or ArcticDEM surface elevations and BedMachine v2 or v3 bed elevations, and any range of k values, we are unable to match the Lindbäck et al. (2015) basin. Instead all our basins resemble those the basin shown in Fig ??.

4.2.3 GEM Basin Outlets

Six basins from the GEM project have a time-series of runoff , and comparisons between our basin-partitioned RCM runoff and observations show better agreement than for 7. To solve this, we manually select two large ice basins to the south of the Watson River basin(s). We note that these basins are significantly smaller than the Watson River basin , but because the basin is primarily defined by a land surface rather than an ice basin, basin delineation is more accurate. Therefore disagreement here between GEM observation and our product is likely attributable to errors in the RCM runoff, not the basin delineation.

Of the six basins with GEM runoff, the two largest (Zackenberg (Fig ice basin. ??) Modeled and observed discharge agree after including these two basins (Fig. 8), suggesting basin delineation, not stage-discharge or RCM runoff is the primary cause for this disagreement. Furthermore, it is the additional width at lower elevation from the larger basin, not the increased inland high-elevation area, that likely contributes the runoff needed to match the observations, because 85 % of all surface runoff occurs below 1350 m, and almost all below 1850 van As et al. (2017).

There is no way to predict the disagreement between our and observed discharge. The observations are needed to highlight the disagreement. It is also not clear what to do to reduce the disagreement, without the previous efforts by Lindbäck et al. (2015) and Røde Elv Lindbäck et al. (2014). Basin delineation is discussed in more detail in the Uncertainty section (Sect. 4.3.2). The other two "problematic" areas can be detected and improved without observational support.

4.2.3 Leverett Glacier

The Leverett Glacier basin area is 1361 km^2 and 100 % ice (Fig 9a). The partial (last calendar year) discharge time series shows MAR and RACMO agree well with each other and with the observations (Fig. ??)) show most ice basins are overlapped by MAR 9b), with no seasonal dependence (Fig 9c). The 95 % prediction interval for MAR is generally within the 1:5 and 5:1 bands, with a larger spread for RACMO (Fig 9c). High model discharge is 3 % higher than observed in MAR and 25 % higher than observed in RACMO, and the ±95 quantile range is between 0.74 and RACMO ice cells, although two ice basins are not covered by RCM ice cells in the Zackenberg basin , and a without an 1.62 (MAR) and 0.82 and 2.02 (RACMO). Low model discharge is also centered near the observations, but as always larger errors exist for low discharge (Fig 9d).

This basin is problematic because the basin feeding the outlet is small (< 5 km^2), but even without the observational record satellite imagery shows a large river discharging from the ice sheet here. Meanwhile, a large (100s of km^2) ice basin does have RCM ice cells in the Røde Elv basin . The four smallest GEM basins discharge just a few 100 m away, but not upstream of this gauge location. We therefore adjust the gauge location onto the ice so that our database access software selects what appears to be the correct basin given the size of the stream in the satellite imagery (Fig. **??**)have only one MAR and RACMO ice cell over an ice basin, several ice basins with no simulated runoff, and several MAR and RACMO ice cells with no co-located ice basin. The discussion of how these (mis)alignments are treated is in Sec. **??**9).

We show both daily time-series (Fig. **??**) and 10-day smoothed scatter-plot (Fig. **??**) of the six GEM basin runoff observations and estimates. We use only MAR as the comparison here because the MAR product includes landand ice runoff, while RACMO only includes ice runoff. The daily time series, limited to 2017 because that is the only yearof Røde Elv data, shows an agreement in both magnitude and variability between the MAR and GEM runoff products. However, all basins except Zackenberg show a The plots shown here use the adjusted gauge location and modeled discharge appears to match the observed discharge. When plotting (not shown) the modeled discharge for the outlet just upstream of the true gauge location, results are clearly incorrect. This issue - small basins at the margin and incorrect outlet location - is persistent throughout this product and discussed in more detail in Sect. 4.3.2.

The Leverett Glacier basin is a subset of the Watson River outlet basin (Sect. 4.2.2). The strong agreement here supports our claim that the Watson River disagreement is not from the RCM runoff or the stage-discharge relationship, but more likely due to basin area. The correct Watson River basin should include some basins outside of the Leverett Glacier basin that still drain to the Watson River outlet gauge location.

4.2.4 Kiattuut Sermiat

The Kiattuut Sermiat discharge basin area is 693 km^2, of which 391 km^2 (56 %) are land and 302 km^2 (44 %) are ice. The basin area is incorrectly large because the land basin reported and shown includes the entire basin that contains the discharge point, of which some is downstream (Fig 10a). However, only ~25 % of runoff comes from the land, and only a small portion of the land basin is downstream of the gauge location, so this is not enough to explain the discharge vs. observation disagreement. The partial (last calendar year) discharge time series shows MAR step-change decrease between day 168 and 169, after which variability continues to match (e.g. modeled vs. observed day-long precipitation events roughly align) but magnitude does not agree as well as prior to day 169. RACMO agree well with each other, but are significantly higher than the observations (Fig. 10b). Both low and high discharge are over-estimated, but the 95% quantile range are within a factor of five (Fig 10c), with a mean scale factor between 1.71 (RACMO bottom 1/3rd of discharge) to 2.47 (MAR high 2/3rds discharge)

The scatter plot has a 10-day smooth applied as in van As et al. (2017), and shows all available days of data not just 2017. Color represents day of year, and similar to Fig. **??** shows that the MAR runoff slightly overestimates the GEM observations early in the year, Kiattuut Sermiat gauge is in a problematic location in terms of determining the actual (non-theoretical) upstream contributing area. Similar to the Leverett Glacier gauge location, the issues here can be estimated independent of observational data. Specifically, it is not clear if this stream includes water from the larger glacier to the east and ENE that feeds this glacier (Fig. 10a) - in our delineation it does not. Furthermore, several glaciers to the NNE and detached from the glacier near the stream gauge appear to drain into a lake that then drains under the glacier with the stream gauge. This latter issue is observable in any cloud-free satellite imagery (for example Google Earth) and slightly underestimates the observations late in the year.

This seasonal disagreement is apparent as a step-change in all years, but not always on day 169 (18 June for non-leap-years) . However, sometime in June of all years where GEM data and MAR data exist and in five of six basins (excluding Zackenberg), a step-decrease in MAR produces an underestimate of runoff relative to observations. The cause for this disagreement is not yet known. does not need the basin delineations provided here to highlight the complexities of this field site. Nonetheless, RCM discharge estimates are only slightly more than double the observations.

The Kiattuut Sermiat gauge location may have been selected in part due to its accessibility - it is walking distance from the Narsarsuaq airport. The data may also suit their intended purpose well and there are likely many results that can be derived independent of the area or location of the upstream source water. However, if the location or area of the upstream contributions are important, then gauge location should balance ease of access and maintenance with the ease with which the data can be interpreted in the broader environment.

4.2.5 Qaanaaq Glacier Outlet

4.2.5 GEM observations near Nuuk

We validate our basins and runoff against one additional observation and highlight that in some locations strong agreement exists but may or may not exist for the right or wrong reason. A small basin near Qaanaaq has been instrumented for the past several summers , with overlap in August 2017.

From Fig. ??, the Qaanaaq glacier outline is closely matched by the ice basin product generated here. However, only one nearby MAR ice cell covers 4 of the 1075 basin grid cells. Even so, that single MAR cell combined with our coverage algorithm (Sec. ??) generates very good agreement between MAR runoff and observations Four Greenland Ecosystem Monitoring Programme (GEM) stream gauges are located near Nuuk with similar basin properties. All are small (7.56 to 37.52 km^2), and 10 % to 25 % ice in the basin mask, but two of the four (Kingigtorssuaq (Fig. 11) and Oriartorfik (Fig. ??). MAR runoff relative to observations ranges from 20 % under (last day of time series) to 140 % over (28 July). When excluding 27 and 28 July where MAR runoff increases prior to observations, maximum overestimate is 50 % on 31 July. The total summed difference between MAR and observations over the course of this time-series is 12 %. 12)) contain small glaciers contributing to observed discharge but no RCM ice cells cover those glaciers, and the remaining two (Teqinngalip (Fig. 13) and Kobbefjord (Fig. 14)) have several small glaciers, but only one per basin has RCM ice coverage.

RACMO ice cells cover almost the entire ice basin, yet RACMO runoff does not agree as well with observations as MAR runoff. The comparison here is among observations from a stream, MAR ice and land, and RACMO ice only. Land area is not included in the RACMO product, but excluding it here is not likely to be the reason for the disagreement given a) All four of these basins show some weak agreement. The maximum r^2 is 0.47 (Fig. 13c) and the relatively small portion of the catchment that is land and b) the magnitude of the MAR-estimated land runoff. Regardless, here RACMO does not capture the 5-fold increase seen in both the MAR and observations. The total summed difference between RACMO and observations over the course of this time-series is 43 %. This (dis)agreement among minimum is 0.11 (Fig 11c), but we note that the worst agreement comes from a basin with no glaciers in the RCM domain, and that in all cases the mean high discharge agrees well, suggesting high discharge in these small basins with few small glaciers may be due to rain (captured in the RCMs) rather than warm days and melted ice. These agreements exist even though our modeled discharge comes from the RCMs that are focused on and validated against the large ice Greenland ice sheet.

4.2.6 Remaining observations

Three additional stream gauges remain: Røde Elv, Zackenberg, and Qaanaaq.

The Røde Elv basin is situated at the southern edge of Disko Island (Fig. 6). It has an area of 100 km^2, of which 72 km^2 are land and 28 km^2 are ice (Fig 15a). The partial (last calendar year) discharge time series shows MAR, RACMO, and the observations highlights the uncertainty in the results presented here.

4.2.7 Leverett Glacier Outlet

all in approximately the same range but with high variability (Fig. 15b). Of the few samples here (n = 98), most are within the factor-of-five bands for MAR and a few more are outside the bands for RACMO (Fig. 15c). Mean discharge offset ranges from a scale factor of 0.86 (RACMO low) to 1.93 (MAR low), with high discharge estimates slightly closer to observations - a 48 % and 77 % overestimate for MAR and RACMO respectively (Fig. 15d).

Leverett glacier runoff from 2009 through 2012 (Figs. **??** and **??**)show a range of agreements and disagreements relative to observations . In 2009 and 2010, early season magnitude and variability matches (MAR better than RACMO), but there is more runoff in the models than the observations in July and August when large runoff occurs. All of 2011 is overestimated by the model, except a late August melt spike showing good agreement, albeit a slight lag between the model signals and the observations. The high runoff 2012 yearshows better agreement between models and observations than the previous three years. In all cases, RACMO has significantly higher variability than MARand the observationsThe Zackenberg basin in NE Greenland has an area of 487 km^2, of which 378 km^2 (78 %) are land and 109 km^2 (22 %) are ice (Fig. 16a). The partial (last calendar year) discharge time series shows disagreement between MAR and RACMO that generally bound the observations (Fig. 16b). RACMO-derived discharge is consistently high for low discharge early in the year, but both discharge products fall mostly within the factor-of-five bands (Fig. 16c). For high discharge, mean modeled discharge is 9 % high (MAR) and 24 % low (RACMO), and has worst-case ±95 quantile range low by a factor of 0.29 (Fig. 16d).

4.2.7 Other Proxy Observations

We are unaware of any additional stream gauge observations with open data that support comparison. However, a range of indirect and proxy observations exist, such as Mankoff et al. (2016) and Stevens et al. (2016) who find good agreement between runoff estimates using the same basin delineation theory as used here, observations of fjord salinity, and a plume model driving submarine glacier terminus melt. The Qaanaaq basin in NW Greenland has an area of 13.2 km^2, of which 2.2 km^2 (17 %) are land and 11 km^2 (83 %) are ice (Fig. 17a). The partial (last calendar year) discharge time series shows disagreement between MAR and RACMO that generally bound the observations (Fig 17b). Of the few samples (n = 82), MAR preferentially over-estimates and RACMO under-estimates discharge, but both generally within a factor of 5 (Fig 17c). Mean high discharge offset scale is 1.14 (MAR) and 0.36 (RACMO) from Fig. 17d.

4.3 Uncertainty

The volume of data generated here is such that manually examining all of it or editing it to remove artifacts or improve the data would be time and cost prohibitive. A similar warning is provided with the ArcticDEM data used here. However, any ArcticDEM issues interior to a basin do not impact results here that are aggregated by basin. Any ArcticDEM issues that cross a basin boundary should impact only the part of the basins it intersects.

Uncertainty from RCM inputs and observations are considered external to this work, although they are still discussed below(Sects. 4.3.3 and 4.3.4). In this work, we introduce one new source of uncertainty - the routing model, which exhibits in two different ways: Spatial (basin delineation) and generates both temporal (runoff delay) and spatial (basin delineation) uncertainty.

We do not address the temporal uncertainty quantitatively or numerically in this work - only in discussion throughout the document and in the Mitigation section. Spatial uncertainty is a product of both the input data(the BedMachine bed)and

4.3.1 Temporal uncertainty

The RCMs include a time lag between when water melts in the model and when it leaves a grid cell. RACMO retention occurs only when there is firn cover (no retention when bare ice melts); MAR includes a time delay of up to 10 days that is primarily a function of surface slope (Zuo and Oerlemans, 1996; Yang et al., 2019). However, neither model includes a subglacial system. Properly addressing time delays with runoff requires addressing storage and release of water across a variety of timescales in a variety of media: firn (e.g. Munneke et al. (2014); Munneke et al. (2019)), supraglacial streams and lakes (e.g. Zuo and Oerlemans (1996); Zuo and Oerlemans (2015); Zuo and Oerlemans (2019)), the subglacial system (e.g. Rennermalm et al. (2013) possibly terrestrial streams and lakes (e.g. van As et al. (2018)) and a variety of other physical processes that are not within the scope of surface mass balance (SMB) modeling. Runoff delay can be implemented outside the RCMs (e.g. Liston and Mernild (2012); Listo but for this version of the product we assume that once an RCM classifies meltwater as "runoff", it is instantly transported to the outlet. Actual lags between melt and discharge range from hours to years (Colgan et al., 2011; van As et al., 2017; Rennermalm et al., 2013; Livingston et al., 2013).

Data released here includes no additional lag beyond the RCM lag, although a 7-day running mean (van As et al., 2017) is included in all of the results presented here except Fig. 6 which shows monthly summed data, and Fig. 4 which shows yearly summed data. When increasing the signal to noise by summing by year (Fig. 4 vs. Fig. 3), model results more closely match observations.

4.3.2 Basin uncertainty

Basin uncertainty is a function of the subglacial routing assumptions (the k value in Equation 2). Estimating these uncertainties may or may not lead to different estimates of runoff parameter in Eq. 2, which in reality varies in both space and time). However, basin uncertainty does not necessary translate to discharge uncertainty. For example, two large almost-overlapping ice basins may change their outlet location by one or a few grid cells between two k values, with a new micro-basin occupying the same outlet as one of the old basin outlets. Large variation in discharge between one of these theoretical large basins and its "replacement" at the same outlet for a different k is not an appropriate estimate of uncertainty - rather the two large almost entirely overlapping basins, but with different outlets, should be compared. This fluidity of basins and outlets between k-scenarios makes it almost impossible to define, identify, and compare basins between scenarios, unless working manually with individual basins (as we did, for example, two drastically different drainage basins from different at the Leverett Glacier observation location, modeled upstream basin, and adjusted upstream basin (see Sect. 4.2.3)).

Another example is that for two different k -values may have similar estimates of runoff. The inverse is less common values, the same ice outlet may theoretically have two different upstream basins that only overlap at the single grid cell containing the outlet, but otherwise have no overlap, yet these two basins (possibly of different size) may have the same discharge values. Put differently, although inland grid cells may change their outlet location by large distances under different routing assumptions (Fig. 2), that does not imply upstream basin area changes under different routing assumptions. Large changes in upstream catchment area are possible (Chu et al., 2016), but we note Chu et al. (2016) highlight changes at only a few outlets and under the extreme scenario of $k = 1.11$ describing an over-pressured system. Because $\rho_w/\rho_i = 1.09$, setting $k = 1.09$ reduces Eq. 2 to $h = z_s$, and is equivalent to an over-pressured system with surface routing of the water. In a limited examination comparing our results with $k \in [0.8, 0.9, 1.0]$, we did not detect basins with large changes in upstream area. In addition all time series graphics show the mean RCM discharge for $k = 1.0$, but the uncertainty among all three k values (not shown) is small enough it is usually difficult to distinguish the three separate uncertainty bands - it is not likely to have drastically different outlet runoff estimates from basins with only small changes , because large volumes of runoff usually come from large areasthe difference between RCMs or between RCMs and observations is much larger than uncertainty from the k parameter.

4.3.3 Basin uncertainty and surface vs. subglacial routing

The basins presented here are static approximations based on 100 m resolution surface DEM of a dynamic systemThe above issues are specific to ice basins. Land basin outlets do not change location, and the range of upstream runoff to a land outlet provides one metric of uncertainty introduced by the k parameter. This uncertainty among all three k values is small at ice margin outlets. It is ~~difficult to quantify the uncertainty of the assumptions used here, but~~ even smaller at land outlets which act as spatial aggregators and increase the signal-to-noise ratio.

Below, we discuss the known uncertainties, ranging from least ~~uncertain~~ to most uncertain.

~~Basins comprised of only land~~ The basins presented here are static approximations based on 100 m resolution surface DEM of a dynamic system. Land basin boundaries are likely to be more precise and accurate than ice basins, because ~~land~~ the land surface is better resolved, has larger surface slopes, has negligible sub-surface flow, and is less dynamic than ~~ice~~the ice surface. Even if basins and outlets seem visually correct from the 100 m product, the basin outline still has uncertainty on the order of hundreds of meters and will therefore include many minor errors and non-physical properties, such as drainage basin boundaries bisecting lakes. However, all artefacts we did find are significantly smaller than the resolution of the 1 km^2 RCM inputs. We do not show but note that when doing the same work with the 150 m BedMachine land surface DEM, some basins change their outlet locations significantly - draining on the opposite side of a spit or isthmus and into a different fjord than the streams do when observed in satellite imagery. We have not observed these errors in streams and basins derived from the 100 m ArcticDEM in a visual comparison with Google Earth, although they may still exist.

~~Basins delineated using the ice surface are likely to be more precise than basins using static subglacial theory, because the ice surface elevation has smaller errors than the bed elevation. However, even if more precise, they may be less accurate, because most water routes subglacially. Finally, the precision and accuracy differences increase when one considers that~~ Moving from land basins to subglacial ice basins, the uncertainty increases because subglacial routing is highly dynamic on timescales from minutes to seasons (e.g. Werder et al. (2013)). This dynamic system may introduce large spatial changes in outflow location (water or basin "piracy", Ahlstrøm et al. (2002); Lindbäck et al. (2015); Chu et al. (2016)), but ~~recent work by~~ Stevens et al. (2018) suggests basins switching outlet locations may not be as common as earlier work suggests, and our sensitivity analysis ~~(Fig. **??** and Appendix) suggests that for source locations~~ suggests that near the margin where the majority of runoff occurs, outlet location ~~change~~ often changes by less than 10 km under different routing assumptions ~~and data sets. Subglacial routing also increases opportunities for subglacial storage~~ .

~~We note that the ice surface is responsible for ~90 % of the subglacial routing assuming equal gradients at the ice surface and base. If basal features are ~10x the size of surface features, then the ice surface is effectively responsible for ~50 % of subglacial routing.~~

~~Finally, subglacial routing introduces hydraulic jumps because the BedMachine bed and thickness products, the Citterio and Ahlstrøm (20 ice and land mask, and the ArcticDEM ice surface are not all perfectly aligned.~~

~~Given all of the above considerations, we opted for surface routing rather than subglacial (similar to Ahlstrøm et al. (2017) and Mernild et al. (2018)). However, we compare surface and subglacial basins (even with hydraulic jumps), and the influence of those basins on the final outflow location, across avariety of products, where we quantify for every grid cell how far the eventual outlet for that grid cell moves under different basindelineation schemes.~~

~~When routing subglacially, we define the head h as~~

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

where h is the hydraulic head at each location, z_b the ice-free land surface and basal topography, k the flotation fraction, ρ_i the density of ice (917 kg m^{-3}), ρ_w the density of water (1000 kg m^{-3}), and z_s the land surface for both ice free and ice covered surfaces. Equation 2 comes from Shreve (1972) where they define the hydropotential (units Pa) , but here is divided by gravity g times the density of water ρ_w to convert the units from units Pa to m. Equation 2 makes the assumption that when ice is present ($z_s \neq z_b$) all water routes subglacially. When (Fig. 2). The largest (> 100 km) changes in outlet location in Fig. 2 occur when the continental or ice flow divides move, and one or two of the k is equal to $\rho_w/\rho_i \approx 1.0905$, then Eq. 2 simplifies to $h = z_s$scenario(s) drain cells to an entirely different coast or sector of the ice sheet.

Fig. **??**, comparing ArcticDEM surface routing vs. BedMachine surface routing, shows that part of one basin shifts its coastal outlet by 30 to < 100 km, a few smaller portions of basins shift their outlets by 10 to < 30 km, Sermeq Kujalleq (Jakobshavn Isbræ) by 3 to The regions near the domain edges - both the land coast and the ice margin - are covered by many small basins, and in this work basins < 10 1 km^2 are absorbed into their largest neighbor (see Methods section). By definition these basins are now hydraulically incorrect. An example can be seen in the Zackenberg basin (Fig. 16a, and southwest corner of the basin), where one small basin on the southern side of a hydraulic divide was absorbed into the large Zackenberg basin that should be defined by and limited to the northern side of the majority by < 1 km. A range of additional routing scheme and input data set comparisons are shown in the Appendix. mountain range.

Finally, even when we perform surface routing for basin delineation, we provide the BedMachine elevation of each outlet . Outlet elevations less than 0 indicate marine terminating subglacial outlets. However, even though this method provides an estimate of the initial subglacial discharge depth, much work remains to determine the effective depth of subglacial discharge, where effective depth is defined as the neutrally buoyant isopycnal that Near the ice margin quality issues exist. At the margin, many of the small basins (absorbed or not) may be incorrect because the relative uncertainty between the bed to the subglacial discharge rapidly reaches once it enters the fjord (c.f. Mankoff et al. (2016))surface increases. Minor mask mis-alignments may cause hydraulic jumps (waterfalls) at the margin, or sinks that then need to be filled by the algorithm, and may overflow away from the real stream. The solution for individual outlets is to visually examine modeled outlet location, nearby streams in satellite imagery, and the area of upstream catchments, as we did for the Leverett Glacier outlet (Sect 4.2.3). Alternatively, selecting several outlets in an area will likely include the nearby "correct" outlet. This can be automated and an effective method to aggregate all the micro-ice basins that occur at the domain edge is to select the downstream land basin associated with one ice outlet, and then all upstream ice outlets for that land basin.

4.3.3 RCM uncertainty

In addition to the basin delineation issues discussed above, the runoff product from the RCMs also introduces uncertainty into the product generated here. The RCM input products do not provide formal time- or space-varying error estimates, but of course do contain errors because they do not precisely nor accurately capture represent a simplified and discretised reality. RCM uncertainty is assigned a fixed value of shown here with a value of ±15 %.

The primary RCM issues include 1) general calibration error, 2) treatment of the time delay for runoff, and 3) low resolution in the spatial grid (sub-grid processes are not captured sufficiently and are often parameterized to agree with limited available observations e.g. density of fresh snow).

The first issue is highlighted above where we compare our runoff to observations, and see for example annually repeating step-changes in RCM runoff that do not match observations.

For the second issue, the RCMs do calculate refreezing in snow and firn, and the RACMO runoff equation does include a retention term, but retention only occurs when there is firn cover. MAR includes a time delay of up to 10 days that is primarily a function of surface slope . Neither model includes the subglacial system and runoff is assumed to immediately leave the ice sheet surface. Properly addressing time delays with runoff requires addressing storage and release of water across a variety of timescales in a variety of media: firn The MAR uncertainty comes from an evaluation by the Greenland SMB Model Intercomparison Project (GrSMBMIP; Fettweis et al. (2020)) that examined the uncertainty of modelled SMB for 95% of the 10767 in-situ measurements over the main ice sheet. 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 time scale. The RACMO uncertainty comes from an estimated average 5% runoff bias in RACMO2.3p2 compared to annual cumulative discharge from the Watson River (Noël et al., 2019). The bias increases to a maximum of 20% for extreme runoff years (e.g. Munneke et al. (2014); Munneke et al. (2019)), supraglacial streams and lakes (e.g. Zuo and Oerlemans (1996); Zuo and Oerlemans (2015); Zuo and Oerlemans (2019)), the subglacial system (e.g. Rennermalm et al. (2 and a variety of other physical processes that are not within the scope of SMB modeling. Runoff delay can be implemented outside the RCMs (e.g. Liston and Mernild (2012); Liston and Mernild (2018)), but for this version of the product we present instantaneous runoff and downstream users can apply temporal lags if needed2010 and 2012), so here we select 15 %, a value between the reported 5 % and the maximum 20 % that matches the MAR uncertainty. We display ±15 % uncertainty in the graphics here and suggest this is a minimum value for daily runoff data.

The third issue is a current limitation of the RCMs that will be improved as future versions increase resolution15 % RCM uncertainty is represented graphically in the time series plots when comparing to each of the observations. It is not shown in the scatter plots because the log-log scaling and many points makes it difficult to display. In the time series plots, we show the mean value from the $k = 1.0$ scenario, and note that discharge from the other two k scenarios covered approximately the same range.

4.3.4 Observational Uncertaintyuncertainty

When comparing against observations, additional uncertainty is introduced because the stage-discharge relationship is neither completely precise or accurate. We use published observation uncertainty when it exists. Only two observational data sets come with uncertainty: Watson River and Qaanaaq. Similar to the RCM uncertainty, they are displayed in the time series but not the scatter plot for each observation graphic.

4.3.5 Mitigating Uncertaintiesuncertainties

Traditional uncertainty propagation is further complicated because it is not clear to what extent the three uncertainties (observational, RCM, and routing model) should be treated as independent from each other - all three uncertainties are likely to show some correlation with elevation, slope, air temperature, or other shared physical processes.

Many of the uncertainties discussed here can be mitigated by increasing the signal to noise ratio of the productprovided here. Because we provide a high spatial and temporal resolution product, this is equivalent to a large number of many signals, each of which has some uncertainty (noise). Averaging results spatially or temporally, if possible for a downstream use of this product, will increase the signal to noise ratio and reduce uncertainty.

For example, because we provide basins for the entire ice sheet, total runoff discharge is not subject to basin uncertainty. Any error in the delineation of one basin must necessarily be corrected by the inclusion (if underestimate) or exclusion (if overestimate) of a neighboring basin, although neighboring basins may introduce their own errors. Therefore, summing basins reduces the error introduced by basin outline uncertainty, and should be done if a downstream product does not need an estimate of runoff discharge from a single outlet. This feature is built-in to coastal outlet discharge which is not as sensitive to our routing algorithm as ice margin outlet discharge because most coast outlets include a range of upstream ice margin outlets (e.g. Figs. ?? vs. ?? in AppendixFig. 7 v. 9). Conversely, at the ice margin, outlet location and discharge volume is more uncertain than at the land coast. However, most runoff is generated near the ice margin and as runoff approaches the margin, there is less opportunity for it to switch basins are fewer opportunities to change outlet location (Fig. 2).

Our coverage algorithm only fills in glaciated regions that have at least some RCM coverage. When working with basins that have glaciated areas and no RCM coverage as in the case for all four of the GEM outlets near Nuuk, discharge can be approximated by estimating discharge from the nearest covered glaciated area with a similar climatic environment.

Temporally, errors introduced by this study's assumption of instantaneous runoff discharge can be reduced by summing or averaging runoff discharge over larger time periods, or applying a lag function to the time series as done here and in van As et al. (2017). Although a given volume of water may remain in storage long term, the assumption of steady statestorage means that if one assumes that storage is roughly steady state, then long-term storage shown by, for example, dye trace studies, can be ignored - the volume with the dye may be stored, but a similar volume should be discharged in its place.

4.3.6 Quality control

The scale of the data are such that manual editing to remove artifacts is time and cost prohibitive. Here we provide one example of incorrect metadata. The elevation of each outlet is included as metadata by looking up the bed elevation in the BedMachine data set at the location of each outlet. Errors in BedMachine or in the outlet location (defined by the GIMP ocean mask) introduce errors in outlet elevation.

A large basin in NW Greenland has metadata outlet elevation > 0 (gray in Fig. 1) but appears to be marine terminating when viewed in satellite imagery. Elsewhere the land vs. marine terminating color coding in Fig. 1 appears to be mostly correct, but this view only provides information about the sign of the elevation, not the magnitude (i.e. if the reported depth is correct). Ice outlets can occur above, at, or below 0 m. It is easier to validate the land terminating basins, which should in theory all have an outlet elevation of 0 m. That is not the case (Fig. 18). It is possible for land outlets to be correctly assigned an elevation > 0 m, if a land basin outlet occurs at a waterfall off a cliff (as might occur the edges of Petermann fjord) or due to DEM discretization of steep cells. However, most of the land outlets at elevations other than 0 are likely due to mask misalignment pushing the coast into fjords (negative land elevation) or inland (positive land elevation). The bulk of land discharge does occur within the 10 m bin at 0 m elevation. More than 75 % of land outlets occur within ± 10 m, and 90 % within 30 m (Fig. 18).

4.4 Other sources of freshwater

The liquid water ~~runoff~~ discharge product provided here is only one source of freshwater that leaves the ice sheet and affects fjords and coastal seas. The other primary freshwater source is iceberg calving and submarine melt at the ice/ocean boundary of marine terminating glaciers. A companion to the liquid water ~~runoff~~ discharge product introduced here is provided by **?**, which estimates solid ice volume flow rates across gates near marine terminating glaciers. That ~~ice downstream~~ downstream ice enters fjords as either calving icebergs or liquid water from submarine melting.

Both this product and **?** provide liquid or solid freshwater volume flow rates at outlets (this product~~, which includes elevation of discharge, equal to depth when negative~~) or grounding lines (Mankoff et al., 2020), but actual freshwater discharge into a fjord occurs at a more complicated range of locations. Solid ice melts throughout the fjord and beyond (e.g. **??**), and the freshwater discharge presented here may enter at ~~a depth~~ the reported depth (Sect. 4.3.6), but rapidly rises up the ice front and eventually flows into the fjord at some isopycnal (see Mankoff et al. (2016)). The eventual downstream location of the fresh water is not addressed in this work.

Freshwater inputs directly to the water surface are also not included in this product. The flux (per square meter) to the water surface should be similar to the flux to the non-ice-covered land surface - assuming the orographic effects on precipitation produce similar fluxes to the near-land water surface. ~~The land runoff volume accounts for ~35 % of the total runoff volume presented in this work (Fig. ??), so the freshwater input (i.e. precipitation) directly to the fjord surface may be of similar magnitude.~~

Finally, basal melt from 1) geothermal heating (e.g. Fahnestock et al. (2001)) 2) frictional heating (e.g. Echelmeyer and Harrison (1990)) and 3) viscous heat dissipation from all previous freshwater sources (c.f. Mankoff and Tulaczyk (2017)) contributes ~~up to 10 % additional runoff~~ additional discharge (see for example Jóhannesson et al. (2020)) to the surface melt. Geothermal and frictional heating are approximately in steady state and contribute freshwater throughout the winter months.

~~Importantly, ice sheet runoff may not be the majority source of freshwater into some fjords, even though it is traditionally considered the majority, or even only, source of freshwater. The combination of land runoff, freshwater inputs (snow and rain) directly onto the near-land fjord surface, and basal runoff, suggests that GIS-wide ice sheet surface runoff may account for < 50 % of total freshwater input. The percent contribution of ice sheet surface runoff to total freshwater input is likely to vary widely depending on the area considered for the downstream fjord.~~

4.5 Summary

Of the 20 comparisons between the two RCMs and the 10 observations,

- In general this product shows good agreement between observations and the modeled discharge from the RCM runoff routed to the outlets, when comparing across multiple basins, especially when ignoring small basins with small glaciers that are not included in the RCMs (Fig. 3). The agreement is not as good when estimating the discharge variability within individual basins. From this, the product is more appropriately used to estimate the magnitude of the discharge from any individual basin, and perhaps provide some idea of the statistical variability, but not necessarily the precise amount of discharge for any specific day.
- The majority of the ~~upstream~~ 20 comparisons have the 95 % prediction interval between scales of 1:5 and 5:1. From this, the model results match observations within plus-or-minus a factor of five, or half an order-of-magnitude. Put differently, the daily RCM values for single or few basins have an uncertainty of +500 % or -80 %.
- The uncertainty of +500%/-80% is for "raw" data: daily discharge for one or few basins with a simple temporal lag. When averaging spatially or temporally over larger areas or longer times, uncertainty decreases (Sect. 4.3). For example, when moving from daily data (Fig. 3) to annual sum (Fig. 4), the uncertainty is reduced to +100%/-50%.
- The two RCMs agree best with each other for the three observations dominated by large ice domains (Watson River (Sect. 4.2.2 & Fig. 7), Leverett Glacier (Sect. 4.2.3 & Fig. 9) which is a subset of the Watson River basin, and ~~the dates and time-span of the estimates.~~ Kiattuut Sermiat (Sect. 4.2.4 & Fig. 10)). RCMs agree best with observations for ice-dominated basins with well-resolved bed topography in BedMachine (i.e. correct basins modeled in this work) - here only Leverett Glacier (Sect. 4.2.3 & Fig. 9) meets this criterion.
- Runoff errors increase with low discharge (panels 'd' in Figs. 7, 9 to 17).
- For land basins, errors are dominated by RCM runoff uncertainty, and may be systematic (bias).
- For ice basins, errors are dominated by basin uncertainty. Errors between similar-sized and neighboring basins are likely to offset and may even cancel each other. Even so, a conservative treatment might consider errors between basins as random and reduce by the sum of the squares when summing discharge from multiple similar-sized and neighboring basins.

5 ~~Data and Code Availability~~Product description

~~This work in its entirety is available at where it will be updated over time~~These data contain a static map of Greenland's hydrological outlets, basins, and streams and a times-series of discharge from each outlet.

~~A website for post-publication updates is available at where we document ongoing changes to this work and use the GitHub Issues feature to collect suggested improvements, document those improvements as they are implemented, document problems~~

that made it through review, and mention related works not cited here, perhaps due to temporal directionality . This version of The output data are provided in the following formats: The stream data are provided as a GeoPackage standard GIS product and a metadata CSV that includes the stream type (start or intermediate segment), network, stream along-flow length, stream straight length, sinuosity, source elevation, outlet elevation, and a variety of stream indices such as the Strahler, Horton, Shreve, Hack, and other parameters (Jasiewicz and Metz, 2011). We note that the subglacial streams are unvalidated with respect to actual subglacial conduits, and they should be used with caution. The outlet data are also provided as a GeoPackage and CSV, each of which include the outlet ID (linked to the basin ID), the longitude, latitude, EPSG:3413 x and y, and the outlet elevation. The outlet elevation is the BedMachine bed elevation at the outlet location, and users should be aware of quality issues identified in Sect. 4.3.6. The ice outlet metadata includes the ID, lon, lat, x, and y of the downstream land outlet, if one exists. The basin product GeoPackage includes the geospatial region that defines the basin. The metadata CSV includes the basin ID (linked to the outlet ID), and the area of each basin. The time-series discharge product is provided as four NetCDF files per year, one for each domain (ice margin, land coast) and one for each RCM (MAR and RACMO). The NetCDF files contain an unlimited time dimension, usually containing 365 or 366 days, much of the same metadata as the outlets CSV file, including the outlet (a.k.a station) ID, the latitude, longitude, and altitude of the outlet, and a runoff variable with dimensions (station, time) and units $m^3 s^{-1}$.

5.1 Database access software

The data can be accessed with custom code from the raw data files. However, to support downstream users we provide a tool to access the outlets, basins, and discharge for any region of interest (ROI). The ROI can be a point, a list describing a polygon, or a file, with units in longitude,latitude (EPSG:4326) or meters (EPSG:3413). If the ROI includes any land basins, an option can be set to include all upstream ice basins and outlets, if they exist. The script can be called from the command line (CLI) and returns CSV formatted tables, or within Python and returns standard Python data structures (from the `GeoPandas` or `xarray` package).

For example, to query for discharge at one point (50.5 °W, 67.2 °N), the document is generated with git commit version . following command is issued:

Runoff can only change in the future - the true past runoff is fixed - yet different estimates exist of past runoff (e. g. van As et al. (2018); van As et al. (2018), and this work). These differences must be caused by different methods or different inputs to the methods.By fully documenting the inputs, methods, and results we use to estimate runoff `python ./discharge.py --base ./freshwater --roi=-50.5,67.2 --discharge`, this work supports attribution of result differences between different estimates. Both data and code are needed to support reproducibility, which is needed to both quantify and attribute differences. That is, future estimates of past runoff can and should both quantify and attribute differences due to changes in input data and the same methods (RCM inputs or the surface or subglacial digital elevation models (DEMs)used for routing), differences due to changes in hydrological routing algorithms using the same data, or combinations where `discharge.py` is the provided script, `./freshwater` is the folder containing the downloaded data, and `--discharge` tells the program to return RCM discharge (as opposed to `--outlets` which would return basin and outlet information). The program documentation and usage examples are available at http://github.com/mankoff/freshwater (Mankoff, 2020b).

Because the `--upstream` option is not set, the `--discharge` option is set, and the point is over land, the results of this command are a time series for the MAR and RACMO land discharge for the basin containing this point. A small subset (the first 10 days of June 2012) are shown as an example:

time	MAR_{land}	$RACMO_{land}$
2012-06-01	0.043025	0.382903
2012-06-02	5.5e-05	0.095672
2012-06-03	5e-05	0.009784
2012-06-04	9e-06	-0.007501
2012-06-05	0.008212	0.007498
2012-06-06	28.601947	0.607345
2012-06-07	0.333926	0.05691
2012-06-08	0.489437	0.204384
2012-06-09	0.038816	0.167325
2012-06-10	5.1e-05	0.011415

If the `upstream` option is set, two additional columns are added: One for each of the two ~~. Quantification and attribution of these differences in needed to move the community from broadly comparable process studies to operational products that better support downstream research goals~~RCM ice domains. A maximum of six columns may be returned: 2 RCM times (1 land + 1 ice + 1 upstream ice domain), because results are summed across all outlets within each domain when the script is called from the command line (summing is not done when the script is accessed from within Python).

6 ~~Conclusions~~

If the `--outlets` option is set instead of the `--RCM` option, then results are a table of outlets. For example, moving 10 ° east and over the ice,

~~Our new outlet, basin, stream, and liquid water discharge data provide a high spatial (~~`python ./discharge.py --base ./freshwater --roi=-40.5,67.2 --outlets`

results in

index	id	lon	lat	x	y	elev	domain	upstream	$coast_{id}$	...
0	118180	-38.071	66.33	313650	-2580750	-78	land	False	-1	...
1	67133	-38.11	66.333	311850	-2580650	-58	ice	False	118180	...

If the script is accessed from within Python, then the `RCM` option returns an `xarray` `Dataset` of discharge, without aggregating by outlet, and the `outlets` option returns a `GeoPandas` `GeoDataFrame`, and includes the geospatial location of all outlets and outline of all basins, and can be saved to GIS-standard file formats for further analysis.

6 Conclusions

We provide a 100 m) and temporal (spatial resolution data set of streams, outlets, and basins, and a 1 day) resolution estimate of freshwater fluxes into Greenland fjords and coastal seas temporal resolution data set of discharge through those outlets for the entire ice-sheet area from 1979 through 2017. We find an annual average Greenland runoff of 400 ± 30 km^3 ranging from 136 ± 1958 through 2019. Access to this database is made simple for non-specialists with a Python script. Comparing the two RCM-derived discharge products to 10 km^3 in 1992 to 785 ± 59 km^3 in 2012, and displaying and overall increase in both magnitude and variabilitygauged streams shows the uncertainty is approximately plus-or-minus a factor of five, or half an order-of-magnitude, or +500%/-80%, when comparing daily discharge for single or few basins.

Because of the high spatial and temporal resolution, quality issues exist at basin and daily scale that do not exist (individual basins) and temporal (daily) resolution, larger uncertainty exists than when working over larger areas or timestime-steps. These larger areas and times can be achieved through spatial or temporal averaging (or implementing a lag function) of this product.

This liquid freshwater volumetric flow rate product is complemented by a solid ice discharge product (Mankoff et al., 2020). Combined, these provide an estimate of the majority of freshwater (total solid ice and liquid) flow rates from the Greenland ice sheet into fjords and coastal seas, at high temporal resolution and process-level spatial resolution (i.e. glacier terminus for solid ice discharge, stream for liquid discharge).

This estimate of freshwater flux volume flow rate into Greenland fjords aims to support further studies of the impact of freshwater on ocean physical, chemical, and biological properties; fjord nutrient, sediment, and ecosystems; and larger societal impacts of freshwater on the fjord and surrounding environments.

KDM produced this work - wrote the code and the text. APA and DVA helped with discussions of methods and quality control. WC, RSF, and DVA helped with writing. KK and SS supplied Qaanaaq data. XF and BN supplied RCM inputs. KL provided GEM data.

The authors declare that they have no conflict of interest.

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. DEMs provided by the Polar Geospatial Center under NSF-OPP awards 1043681, 1559691, and 1542736. Data from the Greenland Ecosystem Monitoring Programme (GEM) were provided by Asiaq – Greenland Survey, Nuuk, Greenland. We thank Dorthe Petersen (ASIAQ) for help with basin quality control.

7 Code and data availability

The data from this work is available at doi:10.22008/promice/freshwater (Mankoff, 2020a).

The code and a website for post-publication updates is available at https://github.com/mankoff/freshwater (Mankoff, 2020b) where we document ongoing changes to this work and use the GitHub Issues feature to collect suggested improvements, document those improvements as they are implemented, document problems that made it through review, and mention related works not yet published. This version of the document is generated with git commit version 834cd97 .

8 Figures

8.1 Overview

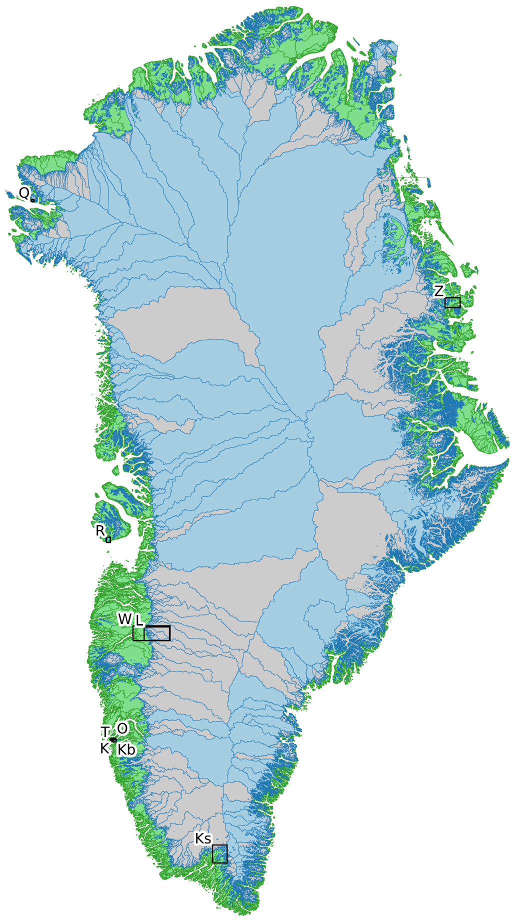

Figure 1. ~~Overview~~ Map of Greenland showing ~~ice~~ all basins ~~(blue)~~ and ~~land~~ the location of 10 gauged streams used for comparison. Land basins ~~(~~shown in green~~)~~. Ice basins in blue when outlet elevation < 0, and ~~insets~~ gray when outlet elevation >= 0 (outlet error elevation is discussed in Sect. 4.3.6). Black boxes and labels mark location of ~~all other figures~~stream gauge observation locations (see Table 1).

8.2 ~~Coverage~~Basin changes with changing k

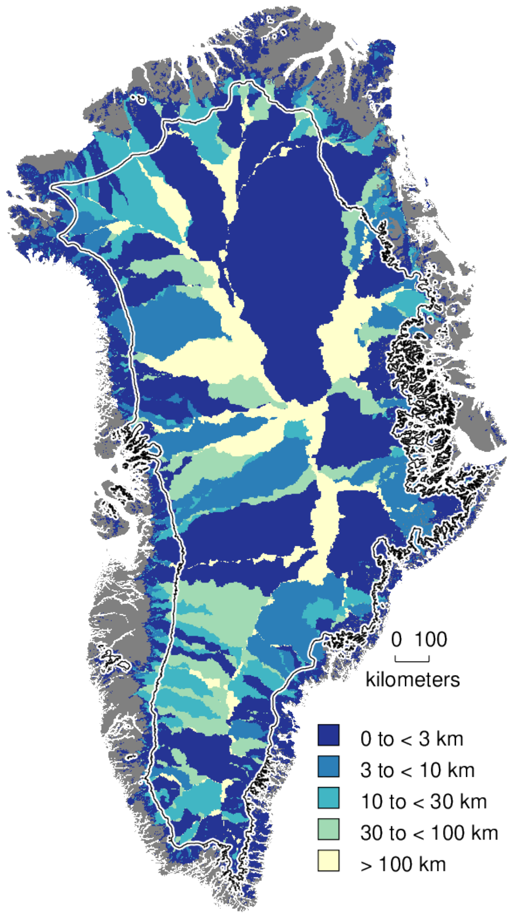

Figure 2. ~~Example~~ Map of ~~model (MAR) and basin misalignment~~ Greenland showing maximum possible distance between outlet locations for all cells, based on three effective basal pressure regimes (~~MAR ice over basin land~~$k \in [0.8, 0.9, 1.0]$, ~~or MAR land over basin ice~~Eq 2). ~~See Sec. ??~~Contour line in Greenland shows 1500 m elevation contour - most runoff occurs below this elevation.

8.3 Bulk observation v. RCM scatter plots

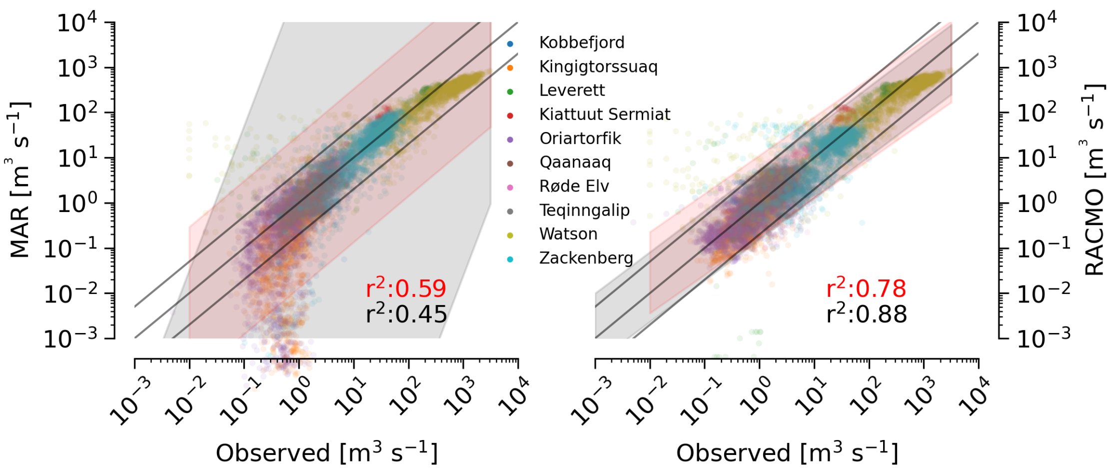

Figure 3. Daily runoff vs. observations for 10 outlets and a total of 17,370 days. Solid lines show 1:1 (center), 1:5 (upper), and 5:1 (lower). Grey band shows 95 % prediction interval. Red band shows 95 % prediction interval when removing the GEM stations near Nuuk (Table 1) that have small glaciers not included in the RCMs

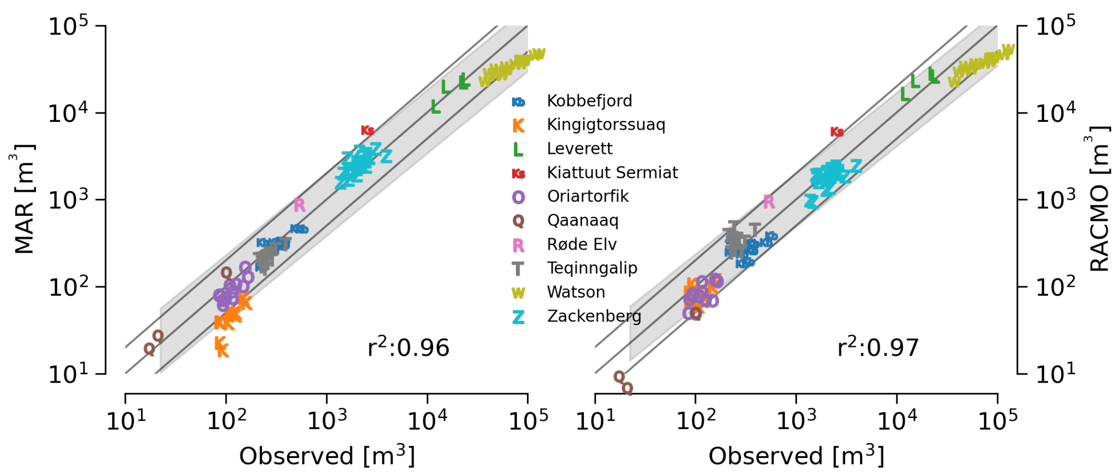

Figure 4. Similar to Figure 3, except here showing annual sum of observed runoff - all days within each year when observations exist are summed. Days without observation are excluded from this comparison. Solid lines show 1:1 (center), 1:2 (upper), and 2:1 (lower). Grey band shows 95 % prediction interval.

8.4 Modified Tukey plot for all observations

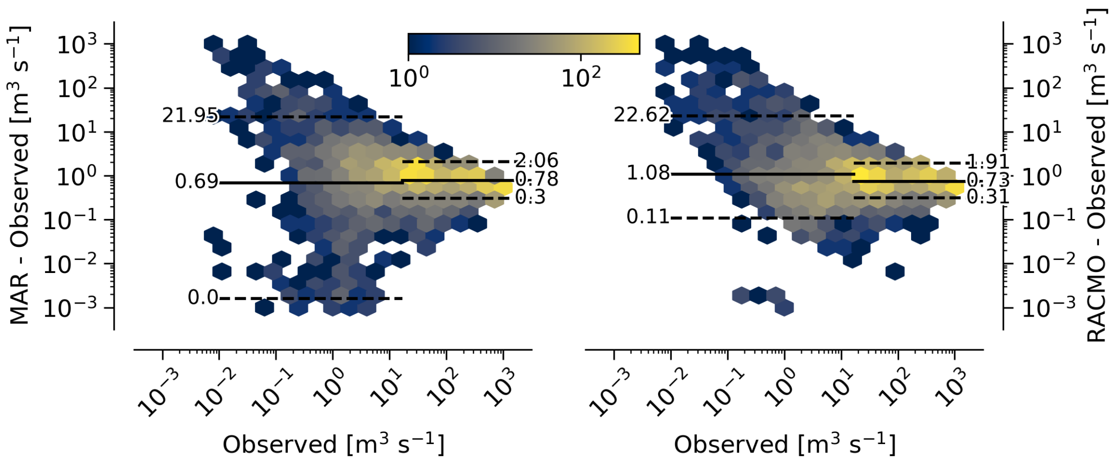

Figure 5. Observation vs. "RCM minus observations" for MAR (left) and RACMO (right), discussed in Sect. 4.2.2. Number of samples at a location is represented by color. Horizontal solid line shows mean, dashed lines ±95 % quantile range, and horizontal split denotes the bottom 1/3 and top 2/3rds quantiles of observed discharge. The four near-Nuuk GEM basins which have glaciers not included in the RCM domain are excluded.

8.5 Annual RunoffBamber 2018

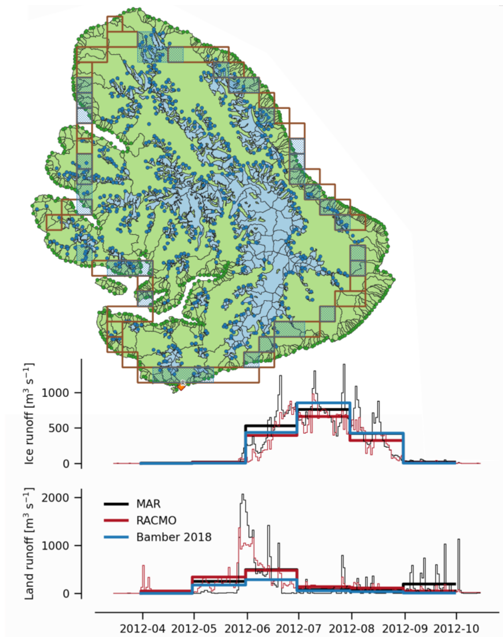

Figure 6. Top panel: Annual Greenland ice sheet runoff from RACMO and MAR as calculated in Disko Island comparison between this product , and B2018 Bamber et al. (2018). Dashed lines show Light green are land basins with dark green outlet dots. Light blue are ice basins with dark blue outlet dots. Brown and hatched blue 5 km^2 cells are the land and ice runoff locations, respectively, from landBamber et al. (2018). Bottom panel: 1999 graphs show ice runoff at daily resolution (thisupper) or monthly and land (lower) runoff for B2018the 2012 runoff calendar year.

8.6 Watson ~~runoff~~River

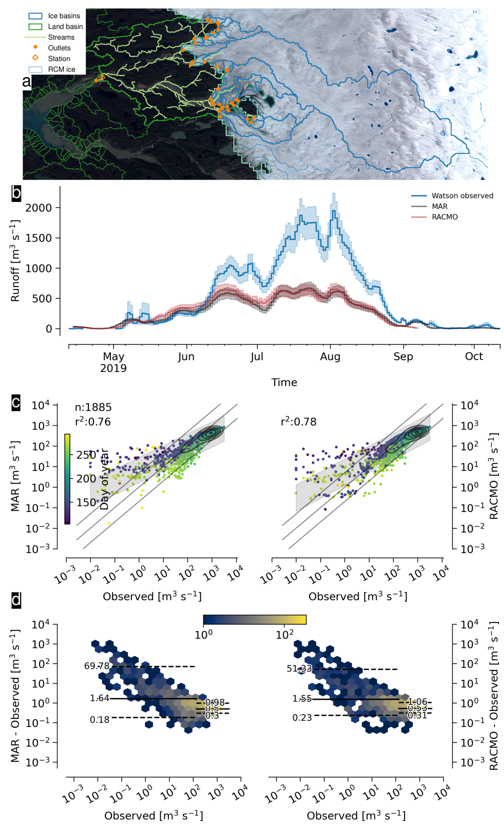

Figure 7. ~~Comparison for~~ Graphical summary of Watson River outlet, basin~~runoff between van As et al. (2018)~~ , and ~~this product~~ discharge (~~this product based on ArcticDEM basin~~ W in Fig. ~~??~~1). ~~Left panel is runoff from the Watson River basin as defined by ArcticDEM~~See Sect. ~~Right panel is runoff from~~ 3.1 for general overview of graphical elements, and Sect. 4.2.2 for discussion of the Watson River basin~~plus the two large basins immediately to the south~~. ~~MAR includes both ice and land contribution to the outlet while RACMO only includes ice contribution~~Basemap from Howat et al. (2014); Howat et al. (2017a).

8.7 Watson basinsAdjustments

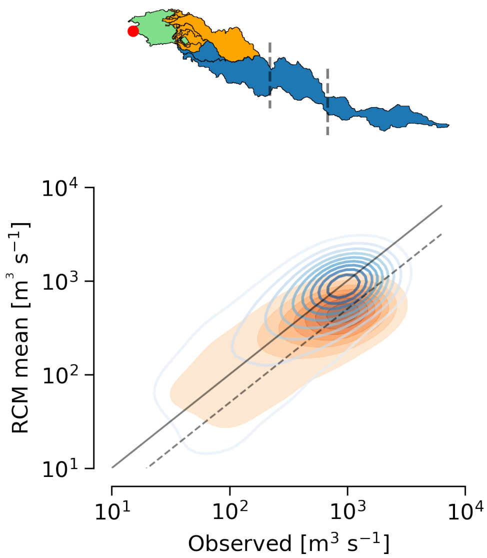

Figure 8. Watson basins based on different routing assumptionsRiver and manually adjusted basin area. ArcticDEM Top panel: map view showing land and ice basin used for "from this work " (green and orange, respectively, same as region shown in Fig7, and two additional basins to the south in blue. ??Vertical dashed lines denote approximate location of 1500 m and 1850 m elevation. Bottom panel: Kernel density estimate (concentration of points) comparing observed vs. average of RACMO and MAR RCM runoff for the default land and ice basin (orange; filled) and with the additional southern basins (blue; lines). Solid and dashed lines are 1:1 and 2:1 (respectively) observed-to-RCM ratios.

8.8 ~~Change in Outlet~~Leverett Glacier

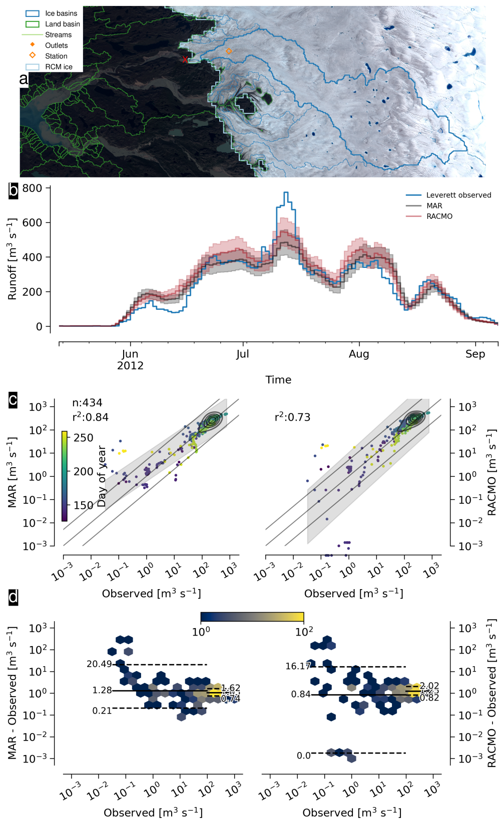

Figure 9. ~~Change in~~ Graphical summary of Leverett Glacier outlet~~location between baseline ArcticDEM surface routing~~ , basin, and ~~BedMachine v3 surface routing is shown for every grid cell. Region is zoomed in near Sermeq Kujalleq~~ discharge (~~Jakobshavn Isbræ~~L in Fig. 1). ~~White-and-black contour line shows 2000 m elevation~~Red X in panel A marks actual observation location, ~~above which little runoff occurs~~but adjusted here to orange diamond within the ice basin. See Sect. 3.1 for general overview of graphical elements, and Sect. 4.2.3 for discussion of the Leverett Glacier basin. Basemap from Howat et al. (2014); Howat et al. (2017a).

8.9 ~~GEM Basin~~Kiattuut Sermiat

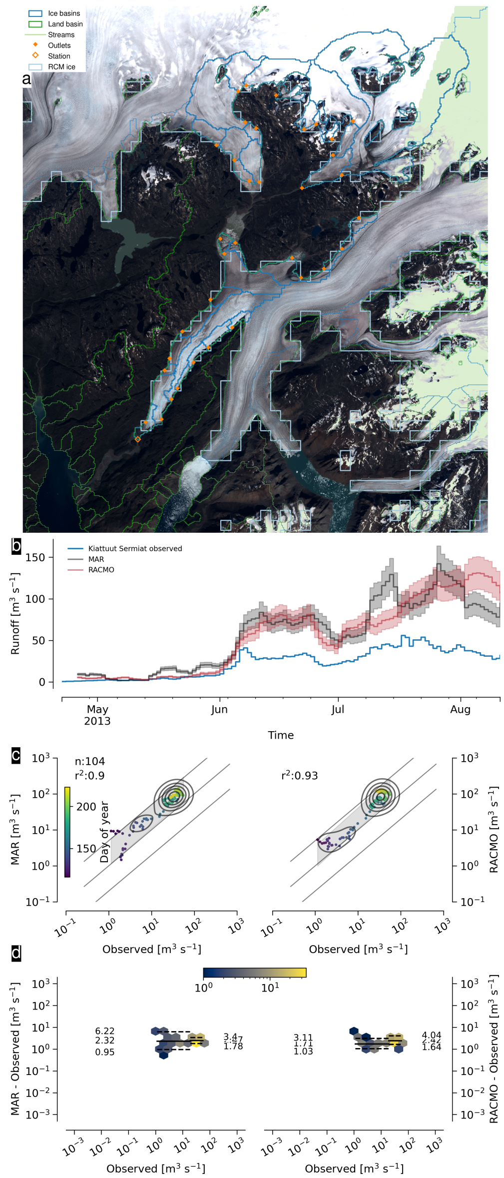

Figure 10. ~~Zackenberg basin for GEM~~ Graphical summary of Kiattuut Sermiat outlet, basin, and discharge (Ks in Fig. ~~Note two small glaciers without correstponding MAR or RACMO ice cells~~1). See ~~Fig~~Sect. ~~??~~ 3.1 for ~~comparisons between GEM and MAR discharge at this location. Also visible is basin artifact at southern-most portion~~ general overview of ~~basin. Because basins < 1 km^2 are absorbed into their largest neighbor~~graphical elements, ~~here small basins clearly outside the basin (south~~ and Sect. 4.2.4 for discussion of the ~~coastal mountain range) are absorbed into the~~ Kiattuut Sermiat basin. Basemap from Howat et al. (2014); Howat (2017a).

8.10 Kingigtorssuaq

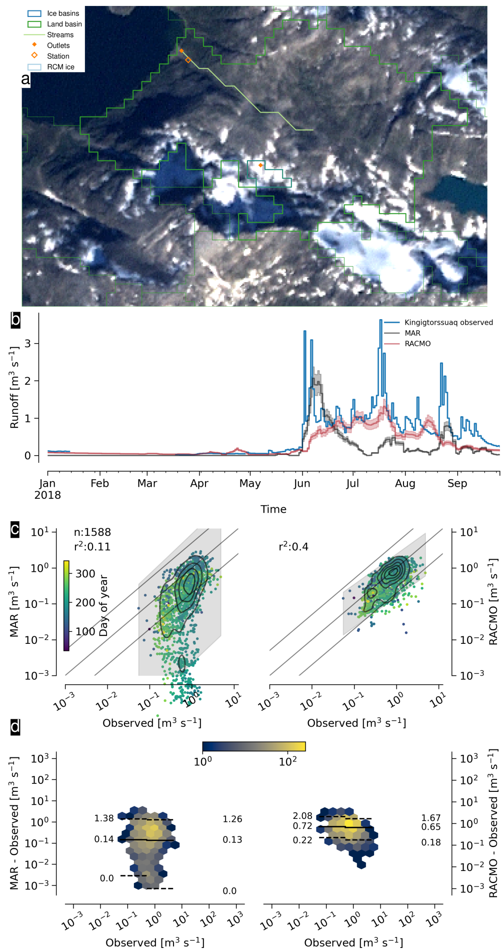

Figure 11. ~~Røde Elv basin for GEM~~ Graphical summary of Kingigtorssuaq outlet, basin, and discharge (K in Fig. 1). See ~~figures ?? and ??~~ Sect. 3.1 for ~~comparisons between GEM~~ general overview of graphical elements, and ~~MAR discharge at this location~~Sect. 4.2.5 for discussion of the Kingigtorssuaq basin. Basemap from Howat et al. (2014); Howat (2017a).

8.11 Oriartorfik

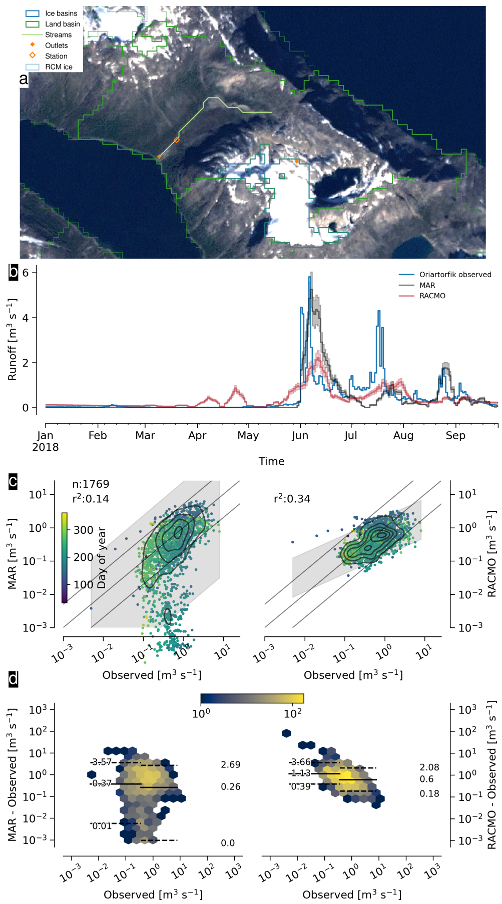

Figure 12. ~~GEM basins for Kingigtorssuaq, Kobbefjord,~~ Graphical summary of Oriartorfik outlet, basin, and ~~Teqinngalip outlets~~discharge (O in Fig. ~~Note that except~~ 1). See Sect. 3.1 for ~~one RCM ice cell~~general overview of graphical elements, ~~no ice basins have RCM runoff estimates~~and Sect. ~~Furthermore, at the eastern edge~~ 4.2.5 for discussion of the ~~image RCM ice cells exist where no ice~~ Oriartorfik basin~~exists (that RCM runoff is discarded). See figures ?? and ?? for comparisons between GEM and MAR discharge at these location~~. Basemap from Howat et al. (2014); Howat (2017a).

8.12 Teqinngalip

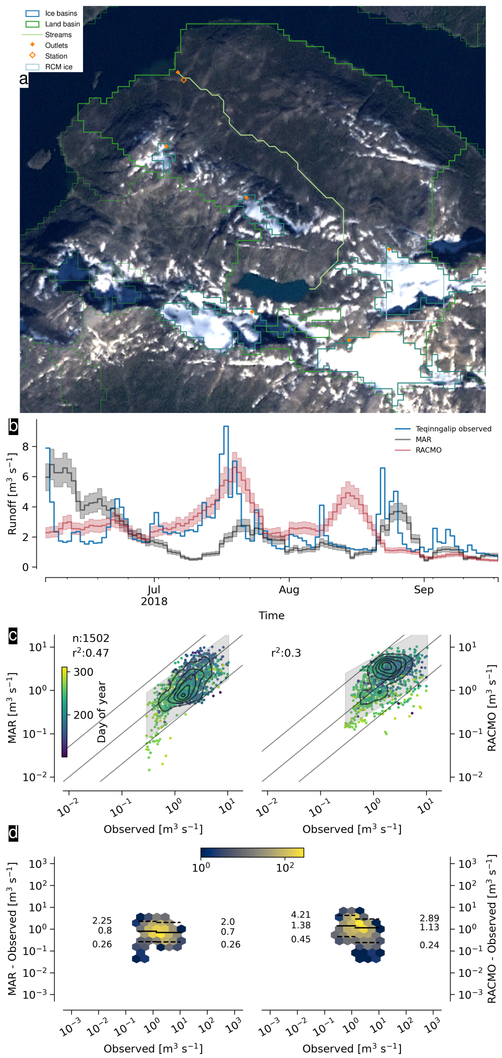

Figure 13. Time series Graphical summary of GEM observed MAR ice Teqinngalip outlet, basin, and land runoff for basins shown discharge (T in Figures ??, ??Fig. 1). See Sect. 3.1 for general overview of graphical elements, and ??Sect. Only 2017 shown because that is 4.2.5 for discussion of the only year where data exists at Røde ElvTeqinngalip basin. Basemap from Howat et al. (2014); Howat et al. (2017a).

8.13 Kobbefjord

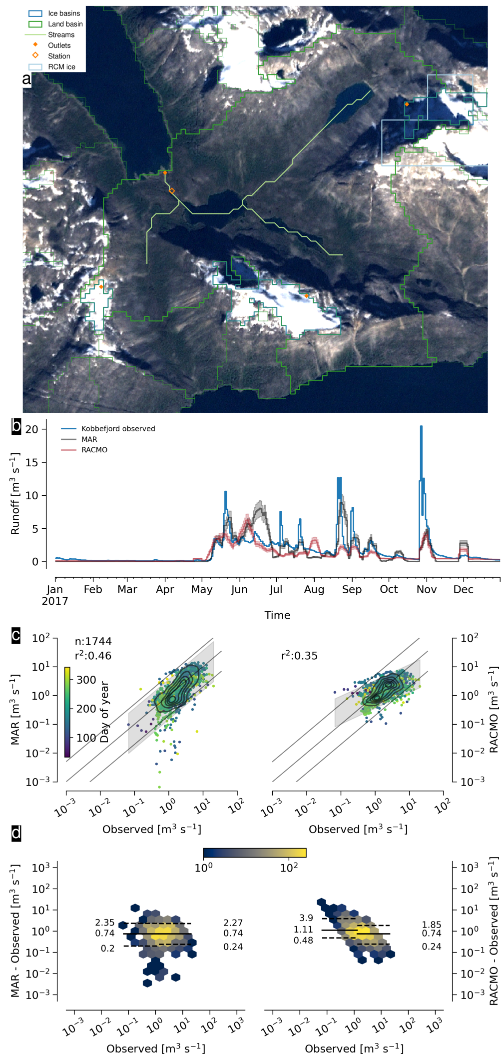

Figure 14. ~~Scatter plot of 10-day averages~~ Graphical summary of ~~GEM~~ Kobbefjord outlet, basin, and ~~MAR runoff for basins shown~~ discharge (Kb in ~~Figures ??, ??~~Fig. 1). See Sect. 3.1 for general overview of graphical elements, and ~~??~~Sect. ~~Data~~ 4.2.5 for ~~all available years at all stations are shown~~discussion of the Kobbefjord basin. Basemap from Howat et al. (2014); Howat et al. (2017a).

8.14 ~~Qaanaaq~~Røde Elv

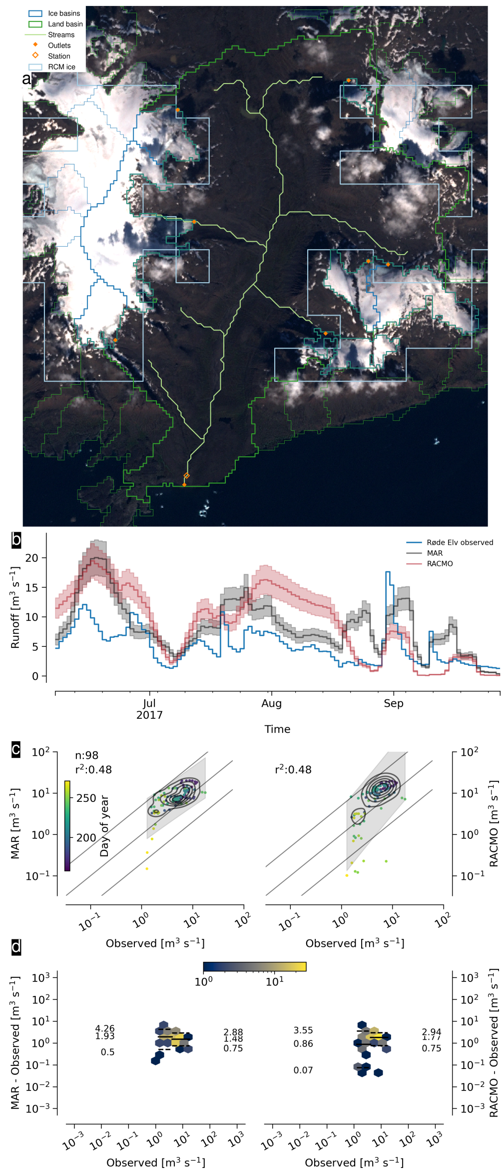

Figure 15. ~~Plan view~~ Graphical summary of ~~Qaanaaq~~ Røde Elv outlet, basin, and discharge (R in Fig. ~~Note that MAR ice cells only cover ~1 %~~ 1). See Sect. 3.1 for general overview of ~~ice basin~~graphical elements, ~~while RACMO ice cells cover ~90 % of ice basin~~and Sect. ~~See Figure ??~~ 4.2.6 for ~~runoff data from this~~ discussion of the Røde Elv basin. Basemap from Howat et al. (2014); Howat (2017a).

8.15 Zackenberg

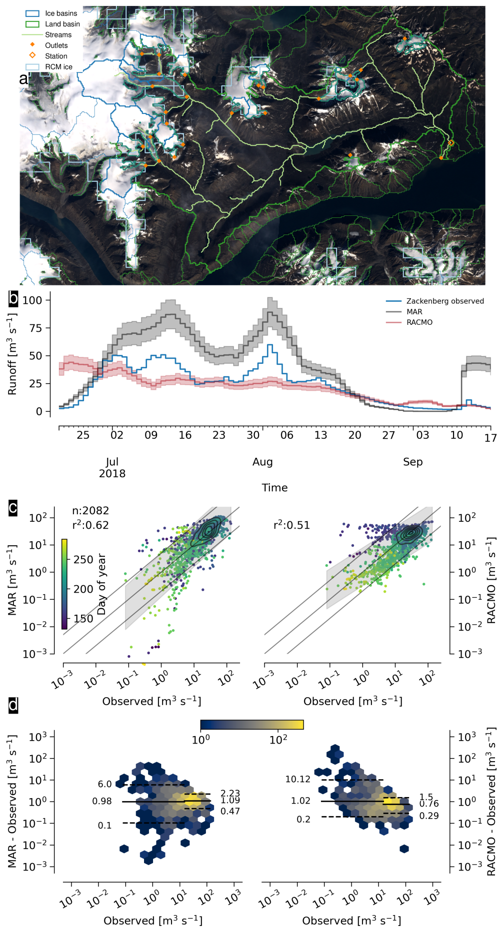

Figure 16. ~~Time series~~ Graphical summary of ~~observed and modeled runoff at Qaanaaq basin~~ Zackenberg outlet, basin, and discharge (~~see Figure ??~~Z in Fig. 1). ~~Displayed uncertainty is 9 %~~ See Sect. 3.1 for ~~observations~~ general overview of graphical elements, and ~~15 % for RCMs~~Sect. ~~Uncertainty only shown~~ 4.2.6 for ~~total MAR runoff, not ice or land components~~discussion of the Zackenberg basin. Basemap from Howat et al. (2014); Howat et al. (2017a).

8.16 ~~Leverett Glacier~~Qaanaaq

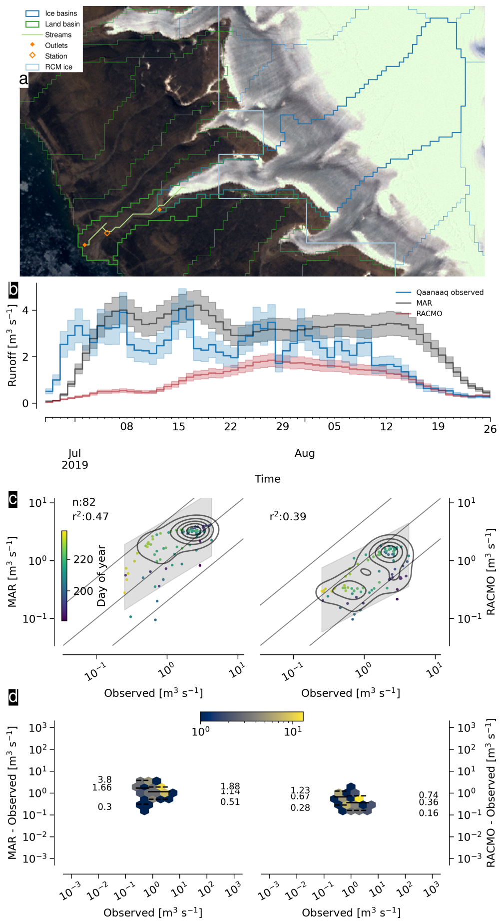

Figure 17. ~~Time series~~ Graphical summary of ~~Leverett glacier observed~~ Qaanaaq outlet, basin, and discharge ~~vs~~(Q in Fig. ~~this product~~1). See Sect. 3.1 for general overview of graphical elements, and Sect. 4.2.6 for discussion of the Qaanaaq basin. Basemap from Howat et al. (2014); Howat et al. (2017a).

8.17 Elevation histogram

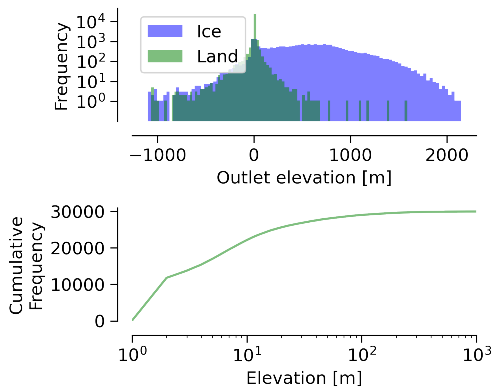

Figure 18. ~~Seatter plot~~ Top: Histogram of ~~Leverett glacier observed discharge vs~~outlet elevations. ~~this product~~Bottom: Cumulative distribution of absolute land outlet elevation. More than 75 % of land outlets occur within ± 10 m, and 90 % within 30 m.

Appendix A: 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), ~~`numpy`~~`geopandas` ~~,~~ (Jordahl et al., 2020), ~~`statsmodel`~~`numpy` (Oliphant, 2006), `x-array` (Hoyer and Hamman, 2017), and `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 (See Supplemental Material). The `parallel` (Tange, 2011) tool was used to speed up processing. We used `proj4` (PROJ contributors, 2018) to compute the errors in the EPSG 3413 projection. The color map for Fig. 2 comes from Brewer (2020).

All code used in this work is available in the Supplemental Online Material.

Author contributions. KDM produced this work - wrote the code and the text. APA and DVA helped with discussions of methods and quality control. WC, RSF, and DVA helped with writing. KK and SS supplied Qaanaaq data. XF and BN supplied RCM inputs. KL provided GEM data.

Appendix B: ~~Changing basins with changing routing schemes~~

~~Same as Fig. ?? but for all of Greenland not zoomed in.~~

~~Same as Fig. ??, but comparing BedMachine surface with Bedmachine 100 % subglacial pressure.~~

~~Same as Fig. ??, but with 90 % subglacial pressure.~~

~~Same as Fig. ??, but with 80 % subglacial pressure.~~

~~Same as Fig. ?? but comparing ice margin outlet change, not coastal outlet change.~~

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

~~Same as Fig. ??, but ice margin outlet rather than coastal outlet. Same as Fig ?? but comparing BedMachine surface with BedMachine 100 % subglacial pressure.~~

Acknowledgements. 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. BN was funded by NWO VENI grant VI.Veni.192.019. DEMs were provided by the Polar Geospatial Center under NSF-OPP awards 1043681, 1559691, and 1542736. Data from the Greenland Ecosystem Monitoring Programme (GEM) were provided by Asiaq – Greenland Survey, Nuuk, Greenland. We thank Dorthe Petersen (ASIAQ) for help with basin quality control.

~~Same as Fig. **??**, but ice margin outlet rather than coastal outlet. Same as Fig **??** but with 90 % subglacial pressure.~~

~~Same as Fig. **??**, but ice margin outlet rather than coastal outlet. Same as Fig **??** but with 80 % subglacial pressure.~~

References

Ahlstrøm, A. P., Petersen, D., Langen, P. L., Citterio, M., and Box, J. E.: Abrupt shift in the observed runoff from the southwestern Greenland ice sheet, Science Advances, 3, e1701 169, https://doi.org/10.1126/sciadv.1701169, http://dx.doi.org/10.1126/sciadv.1701169, 2017.

Ahlstrøm, A. P., Bøggild, C. E., Mohr, J. J., Reeh, N., Christensen, E. L., Olesen, O. B., and Keller, K.: Mapping of a hydrological ice-sheet drainage basin on the West Greenland ice-sheet margin from ERS-1/-2 SAR interferometry, ice-radar measurement and modelling, Annals of Glaciology, 34, 309–314, https://doi.org/10.3189/172756402781817860, http://dx.doi.org/10.3189/172756402781817860, 2002.

Altman, D. G. and Bland, J. M.: Measurement in Medicine: The Analysis of Method Comparison Studies, The Statistician, 32, 307, https://doi.org/10.2307/2987937, http://dx.doi.org/10.2307/2987937, 1983.

An, S.-I., Kim, H., and Kim, B.-M.: Impact of freshwater discharge from the Greenland ice sheet on North Atlantic climate variability, Theoretical and Applied Climatology, 112, 29–43, https://doi.org/10.1007/s00704-012-0699-6, 2012.

Balmonte, J. P., Hasler-Sheetal, H., Glud, R. N., Andersen, T. J., Sejr, M. K., Middelboe, M., Teske, A., and Arnosti, C.: Sharp contrasts between freshwater and marine microbial enzymatic capabilities, community composition, and DOM pools in a NE Greenland fjord, Limnology and Oceanography, https://doi.org/10.1002/lno.11253, http://dx.doi.org/10.1002/lno.11253, 2019.

Bamber, J. L., Griggs, J. A., Hurkmans, R. T. W. L., Dowdeswell, J. A., Gogineni, S. P., Howat, I., Mouginot, J., Paden, J., Palmer, S., Rignot, E., and Steinhage, D.: A new bed elevation dataset for Greenland, The Cryosphere, 7, 499–510, https://doi.org/10.5194/tc-7-499-2013, 2013.

Bamber, J. L., Tedstone, A. J., King, M. D., Howat, I. M., Enderlin, E. M., van den Broeke, M. R., and Noel, B.: Land Ice Freshwater Budget of the Arctic and North Atlantic Oceans: 1. Data, Methods, and Results, Journal of Geophysical Research: Oceans, 123, 1827–1837, https://doi.org/10.1002/2017jc013605, 2018.

Beckmann, J., Perrette, M., Beyer, S., Calov, R., Willeit, M., and Ganopolski, A.: Modeling the response of Greenland outlet glaciers to global warming using a coupled flow line–plume model, The Cryosphere, 13, 2281–2301, https://doi.org/10.5194/tc-13-2281-2019, http://dx.doi.org/10.5194/tc-13-2281-2019, 2019.

Bendtsen, J., Mortensen, J., Lennert, K., and Rysgaard, S.: Heat sources for glacial ice melt in a West Greenland tidewater outlet glacier fjord: The role of subglacial freshwater discharge, Geophysical Research Letters, https://doi.org/10.1002/2015GL063846, 2015.

Brewer, C. A.: ColorBrewer.org Website, http://www.ColorBrewer.org, accessed 2020-06-02, 2020.

Catania, G., Stearns, L., Moon, T., Enderlin, E., and Jackson, R.: Future Evolution of Greenland's Marine-Terminating Outlet Glaciers, Journal of Geophysical Research: Earth Surface, https://doi.org/10.1029/2018jf004873, http://dx.doi.org/10.1029/2018JF004873, 2019.

Chu, W., Creyts, T. T., and Bell, R. E.: Rerouting of subglacial water flow between neighboring glaciers in West Greenland, Journal of Geophysical Research: Earth Surface, 121, 925–938, https://doi.org/10.1002/2015JF003705, 2016.

Citterio, M. and Ahlstrøm, A. P.: Brief communication "The aerophotogrammetric map of Greenland ice masses", The Cryosphere, 7, 445–449, https://doi.org/10.5194/tc-7-445-2013, http://dx.doi.org/10.5194/tc-7-445-2013, 2013.

Citterio, M., Sejr, M. K., Langen, P. L., Mottram, R. H., Abermann, J., Hillerup Larsen, S., Skov, K., and Lund, M.: Towards quantifying the glacial runoff signal in the freshwater input to Tyrolerfjord–Young Sound, NE Greenland, Ambio, 46, 146–159, https://doi.org/10.1007/s13280-016-0876-4, http://dx.doi.org/10.1007/s13280-016-0876-4, 2017.

Colgan, W., Rajaram, H., Anderson, R., Steffen, K., Phillips, T., Joughin, I. R., Zwally, H. J., and Abdalati, W.: The annual glaciohydrology cycle in the ablation zone of the Greenland ice sheet: Part 1. Hydrology model, Journal of Glaciology, 57, 697–709, 2011.

Cowton, T. R., Slater, D., Sole, A., Goldberg, D., and Nienow, P.: Modeling the impact of glacial runoff on fjord circulation and submarine melt rate using a new subgrid-scale parameterization for glacial plumes, Journal of Geophysical Research: Oceans, 120, 796–812, https://doi.org/10.1002/2014JC010324, 2015.

Cowton, T. R., Todd, J. A., and Benn, D. I.: Sensitivity of tidewater glaciers to submarine melting governed by plume locations, Geophysical Research Letters, https://doi.org/10.1029/2019gl084215, http://dx.doi.org/10.1029/2019GL084215, 2019.

Crozier, J., Karlstrom, L., and Yang, K.: Basal control of supraglacial meltwater catchments on the Greenland Ice Sheet, The Cryosphere, 12, 3383–3407, https://doi.org/10.5194/tc-12-3383-2018, http://dx.doi.org/10.5194/tc-12-3383-2018, 2018.

Dask Development Team: Dask: Library for dynamic task scheduling, https://dask.org, 2016.

Delhasse, A., Kittel, C., Amory, C., Hofer, S., and Fettweis, X.: Brief communication: Interest of a regional climate model against ERA5 to simulate the near-surface climate of the Greenland ice sheet, The Cryosphere Discussions, https://doi.org/10.5194/tc-2019-96, https://doi.org/10.5194/tc-2019-96, 2019.

Echelmeyer, K. and Harrison, W. D.: Jakobshavns Isbræ, West Greenland: Seasonal Variations in Velocity - or Lack Thereof, Journal of Glaciology, 36, 82–88, https://doi.org/10.3189/s0022143000005591, 1990.

Fahnestock, M., Abdalati, W., Joughin, I. R., Brozena, J., and Gogineni, P. S.: High geothermal heat flow, basal melt, and the origin of rapid ice flow in central Greenland, Science, 294, 2338–2342, https://doi.org/10.1126/science.1065370, 2001.

Fettweis, X., Box, J. E., Agosta, C., Amory, C., Kittel, C., Lang, C., van As, D., Machguth, H., and Gallée, H.: Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model, The Cryosphere, 11, 1015–1033, https://doi.org/10.5194/tc-11-1015-2017, http://dx.doi.org/10.5194/tc-11-1015-2017, 2017.

Fettweis, X., Hofer, S., Krebs-Kanzow, U., Amory, C., Aoki, T., Berends, C. J., Born, A., Box, J. E., Delhasse, A., Fujita, K., and et al.: GrSMBMIP: Intercomparison of the modelled 1980–2012 surface mass balance over the Greenland ice sheet, The Cryosphere Discussions, https://doi.org/10.5194/tc-2019-321, http://dx.doi.org/10.5194/tc-2019-321, 2020.

Fried, M., Carroll, D., Catania, G., Sutherland, D., Stearns, L., Shroyer, E., and Nash, J.: Distinct frontal ablation processes drive heterogeneous submarine terminus morphology, Geophysical Research Letters, https://doi.org/10.1029/2019gl083980, http://dx.doi.org/10.1029/2019GL083980, 2019.

GDAL/OGR contributors: GDAL/OGR Geospatial Data Abstraction software Library, Open Source Geospatial Foundation, https://gdal.org, 2020.

Gillard, L. C., Hu, X., Myers, P. G., and Bamber, J. L.: Meltwater pathways from marine terminating glaciers of the Greenland ice sheet, Geophysical Research Letters, 43, 10,873–10,882, https://doi.org/10.1002/2016gl070969, http://dx.doi.org/10.1002/2016GL070969, 2016.

GRASS Development Team: Geographic Resources Analysis Support System (GRASS GIS) Software, Open Source Geospatial Foundation, USA, https://grass.osgeo.org, 2018.

Hawkings, J., Wadham, J., Tranter, M., Lawson, E., Sole, A., Cowton, T., Tedstone, A., Bartholomew, I., Nienow, P., Chandler, D., and et al.: The effect of warming climate on nutrient and solute export from the Greenland Ice Sheet, Geochemical Perspectives Letters, p. 94–104, https://doi.org/10.7185/geochemlet.1510, http://dx.doi.org/10.7185/geochemlet.1510, 2015.

Hawkings, J., Wadham, J., Telling, J., Bagshaw, E., Beaton, A., Chandler, D., and Dubnick, A.: Proglacial discharge measurements, Kiattuut Sermiat glacier, south Greenland (near Narsarsuaq), https://doi.org/10.5281/zenodo.3685976, 2016a.

Hawkings, J., Wadham, J., Tranter, M., Telling, J., Bagshaw, E., Beaton, A., Simmons, S.-L., Chandler, D., Tedstone, A., and Nienow, P.: The Greenland Ice Sheet as a hot spot of phosphorus weathering and export in the Arctic, Global Biogeochemical Cycles, 30, 191–210, https://doi.org/10.1002/2015gb005237, 2016b.

Howat, I.: MEaSUREs Greenland Ice Mapping Project (GIMP) 2000 Image Mosaic, Version 1, https://doi.org/10.5067/4RNTRRE4JCYD, updated 2018. Used all subsets. Accessed 2020-02-04. NASA National Snow and Ice Data Center Distributed Active Archive Center, 2017a.

Howat, I.: MEaSUREs Greenland Ice Mapping Project (GIMP) Land Ice and Ocean Classification Mask, Version 1, https://doi.org/10.5067/B8X58MQBFUPA, used all subsets; Accessed 2019-03-21. NASA National Snow and Ice Data Center Distributed Active Archive Center, 2017b.

Howat, I. M., Negrete, A., and Smith, B. E.: The Greenland Ice Mapping Project (GIMP) land classification and surface elevation data sets, The Cryosphere, 8, 1509–1518, https://doi.org/10.5194/tc-8-1509-2014, http://dx.doi.org/10.5194/tc-8-1509-2014, 2014.

Hoyer, S. and Hamman, J. J.: xarray: N-D labeled Arrays and Datasets in Python, Journal of Open Research Software, 5, https://doi.org/10.5334/jors.148, http://dx.doi.org/10.5334/jors.148, 2017.

Hunter, J. D.: Matplotlib: A 2D graphics environment, Computing In Science & Engineering, 9, 90–95, 2007.

Jasiewicz, J. and Metz, M.: A new GRASS GIS toolkit for Hortonian analysis of drainage networks, Computers & Geosciences, 37, 1162–1173, https://doi.org/10.1016/j.cageo.2011.03.003, http://dx.doi.org/10.1016/j.cageo.2011.03.003, 2011.

Jordahl, K., den Bossche, J. V., Wasserman, J., McBride, J., Fleischmann, M., Gerard, J., Tratner, J., Perry, M., Farmer, C., Hjelle, G. A., Gillies, S., Cochran, M., Bartos, M., Culbertson, L., Eubank, N., Bilogur, A., and maxalbert: geopandas/geopandas: v0.7.0, https://doi.org/10.5281/zenodo.3669853, https://doi.org/10.5281/zenodo.3669853, 2020.

Jóhannesson, T., Pálmason, B., Hjartarson, , Jarosch, A. H., Magnússon, E., Belart, J. M. C., and Gudmundsson, M. T.: Non-surface mass balance of glaciers in Iceland, Journal of Glaciology, p. 1–13, https://doi.org/10.1017/jog.2020.37, 2020.

Kamenos, N. A., Hoey, T. B., Nienow, P. W., Fallick, A. E., and Claverle, T.: Reconstructing Greenland ice sheet runoff using coralline algae, Geology, 40, 1095–1098, https://doi.org/10.1130/G33405.1, 2012.

Kanna, N., Sugiyama, S., Ohashi, Y., Sakakibara, D., Fukamachi, Y., and Nomura, D.: Upwelling of Macronutrients and Dissolved Inorganic Carbon by a Subglacial Freshwater Driven Plume in Bowdoin Fjord, Northwestern Greenland, Journal of Geophysical Research: Biogeosciences, 123, 1666–1682, https://doi.org/10.1029/2017jg004248, http://dx.doi.org/10.1029/2017JG004248, 2018.

Kluyver, T., Ragan-Kelley, B., Pérez, F., Granger, B., Bussonnier, M., Frederic, J., Kelley, K., Hamrick, J., Grout, J., Corlay, S., Ivanov, P., Avila, D., Abdalla, S., and Willing, C.: Jupyter Notebooks – a publishing format for reproducible computational workflows, 2016.

Kondo, K. and Sugiyama, S.: Discharge measurement at the outlet stream of Qaanaaq Glacier in the summer 2017-2019, https://doi.org/10.22008/hokkaido/data/meltwater_discharge/qaanaaq, GEUS Data Center, 2020.

Lampkin, D. J. and VanderBerg, J.: A preliminary investigation of the influence of basal and surface topography on supraglacial lake distribution near Jakobshavn Isbrae, western Greenland, Hydrological Processes, 25, 3347–3355, https://doi.org/10.1002/hyp.8170, http://dx.doi.org/10.1002/hyp.8170, 2011.

Langen, P. L., Mottram, R. H., Christensen, J. H., Boberg, F., Rodehacke, C. B., Stendel, M., van As, D., Ahlstrøm, A. P., Mortensen, J., Rysgaard, S., Petersen, D., Svendsen, K. H., Aḥalgeirsdóttir, G., and Cappelen, J.: Quantifying energy and mass fluxes controlling Godthåbsfjord freshwater input in a 5 km simulation (1991-2012), Journal of Climate, 28, 3694–3713, https://doi.org/10.1175/JCLI-D-14-00271.1, 2015.

Langley, K.: GEM river discharge measurements, https://doi.org/10.22008/asiaq/data/meltwater_discharge/gem, GEUS Data Center, 2020.

Lewis, S. M. and Smith, L. C.: Hydrologic drainage of the Greenland ice sheet, Hydrological Processes, 23, 2004–2011, https://doi.org/10.1002/hyp.7343, 2009.

Lindbäck, K., Pettersson, R., Doyle, S. H., Helanow, C., Jansson, P., Kristensen, S. S., Stenseng, L., Forsberg, R., and Hubbard, A. L.: High-resolution ice thickness and bed topography of a land-terminating section of the Greenland Ice Sheet, Earth System Science Data, 6, 331–338, https://doi.org/10.5194/essd-6-331-2014, http://dx.doi.org/10.5194/essd-6-331-2014, 2014.

Lindbäck, K., Pettersson, R., Hubbard, A. L., Doyle, S. H., van As, D., Mikkelsen, A. B., and Fitzpatrick, A. A.: Subglacial water drainage, storage, and piracy beneath the Greenland Ice Sheet, Geophysical Research Letters, https://doi.org/10.1002/2015GL065393, 2015.

Liston, G. E. and Mernild, S. H.: Greenland freshwater runoff. Part I: A runoff routing model for glaciated and nonglaciated landscapes (HydroFlow), Journal of Climate, 25, 5997–6014, https://doi.org/10.1175/JCLI-D-11-00591.1, 2012.

Livingston, S. J., Clark, C. D., Woodward, J., and Kingslake, J.: Potential subglacial lake locations and meltwater drainage pathways beneath the Antarctic and Greenland ice sheets, The Cryosphere, 7, 1721–1740, https://doi.org/10.5194/tc-7-1721-2013, 2013.

Mankoff, K. D.: Freshwater runoff, https://doi.org/10.22008/promice/freshwater, last access: 10 August 2020, 2020a.

Mankoff, K. D.: Freshwater, GitHub https://github.com/mankoff/freshwater, last access: 10 August 2020, 2020b.

Mankoff, K. D. and Tulaczyk, S. M.: The past, present, and future viscous heat dissipation available for Greenland subglacial conduit formation, The Cryosphere, 11, 303–317, https://doi.org/10.5194/tc-11-303-2017, 2017.

Mankoff, K. D., Straneo, F., Cenedese, C., Das, S. B., Richards, C. G., and Singh, H.: Structure and dynamics of a subglacial discharge plume in a Greelandic fjord, Journal of Geophysical Research: Oceans, 121, 8670–8688, https://doi.org/10.1002/2016JC011764, 2016.

Mankoff, K. D., Solgaard, A., Colgan, W., Ahlstrøm, A. P., Khan, S. A., and Fausto, R. S.: Greenland Ice Sheet solid ice discharge from 1986 through March 2020, Earth System Science Data, 12, 1367–1383, https://doi.org/10.5194/essd-12-1367-2020, http://dx.doi.org/10.5194/essd-12-1367-2020, 2020.

Martin Bland, J. and Altman, D. G.: Statistical methods for assessing agreement between two methods of clinical measurement, The Lancet, 327, 307–310, https://doi.org/10.1016/s0140-6736(86)90837-8, http://dx.doi.org/10.1016/S0140-6736(86)90837-8, 1986.

McKinney, W.: Data Structures for Statistical Computing in Python, in: Proceedings of the 9th Python in Science Conference, edited by van der Walt, S. and Millman, J., pp. 51 – 56, 2010.

Mernild, S., Howat, I., Ahn, Y., Liston, G., Steffen, K., Jakobsen, B., Hasholt, B., Fog, B., and van As, D.: Freshwater flux to Sermilik Fjord, SE Greenland, The Cryosphere, 4, 453–465, https://doi.org/10.5194/tc-4-453-2010, 2010a.

Mernild, S. H. and Liston, G. E.: Greenland Freshwater Runoff. Part II: Distribution and Trends, 1960-2010, Journal of Climate, 25, 6015–6035, https://doi.org/10.1175/JCLI-D-11-00592.1, 2012.

Mernild, S. H., Liston, G. E., Hiemstra, C. A., and Steffen, K.: Surface melt area and water balance modeling on the Greenland ice sheet 1995-2005, Journal of Hydrometeorology, 9, 1191–1211, https://doi.org/10.1175/2008JHM957.1, 2008.

Mernild, S. H., Liston, G. E., Hiemstra, C. A., Steffen, K., Hanna, E., and Christensen, J. H.: Greenland Ice Sheet surface mass-balance modelling and freshwater flux for 2007, and in a 1995–2007 perspective, Hydrological Processes, 23, 2470–2484, https://doi.org/10.1002/hyp.7354, 2009.

Mernild, S. H., Liston, G. E., Steffen, K., van den Broeke, M., and Hasholt, B.: Runoff and mass-balance simulations from the Greenland Ice Sheet at Kangerlussuaq (Søndre Strømfjord) in a 30-year perspective, 1979–2008, The Cryosphere, 4, 231–242, https://doi.org/10.5194/tc-4-231-2010, http://dx.doi.org/10.5194/tc-4-231-2010, 2010b.

Mernild, S. H., Liston, G. E., van As, D., Hasholt, B., and Yde, J. C.: High-resolution ice sheet surface mass-balance and spatiotemporal runoff simulations: Kangerlussuaq, west Greenland, Arctic, Antarctic, and Alpine Research, 50, S100 008, https://doi.org/10.1080/15230430.2017.1415856, http://dx.doi.org/10.1080/15230430.2017.1415856, 2018.

Monteban, D., Pedersen, J. O. P., and Nielsen, M. H.: Physical oceanographic conditions and a sensitivity study on meltwater runoff in a West Greenland fjord: Kangerlussuaq, Oceanologia, https://doi.org/10.1016/j.oceano.2020.06.001, http://dx.doi.org/10.1016/j.oceano.2020.06.001, 2020.

Morlighem, M., Rignot, E. J., Mouginot, J., Seroussi, H., and Larour, E.: Deeply incised submarine glacial valleys beneath the Greenland ice sheet, Nature Geoscience, 7, 418–422, https://doi.org/10.1038/NGEO2167, 2014.

Morlighem, M., Williams, C., Rignot, E., An, L., Arndt, J. E., Bamber, J., Catania, G., Chauché, N., Dowdeswell, J. A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T. M., Kjeldsen, K. K., Millan, R., Mayer, L., Mouginot, J., Noël, B., O'Cofaigh, C., Palmer, S. J., Rysgaard, S., Seroussi, H., Siegert, M. J., Slabon, P., Straneo, F., van den Broeke, M. R., Weinrebe, W., Wood, M., and Zinglersen, K.: IceBridge BedMachine Greenland, Version 3, https://doi.org/10.5067/2CIX82HUV88Y, used all subsets; Accessed 2018-10-28, 2017a.

Morlighem, M., Williams, C. N., Rignot, E., An, L., Arndt, J. E., Bamber, J. L., Catania, G., Chauché, N., Dowdeswell, J. A., Dorschel, B., Fenty, I., Hogan, K., Howat, I. M., Hubbard, A., Jakobsson, M., Jordan, T. M., Kjeldsen, K. K., Millan, R., Mayer, L., Mouginot, J., Noël, B. P. Y., Cofaigh, C. Ó., Palmer, S., Rysgaard, S., Seroussi, H., Siegert, M. J., Slabon, P., Straneo, F., van den Broeke, M. R., Weinrebe, W., Wood, M., and Zinglersen, K. B.: BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multi-beam echo sounding combined with mass conservation, Geophysical Research Letters, https://doi.org/10.1002/2017gl074954, 2017b.

Mortensen, J., Bendtsen, J., Motyka, R. J., Lennert, K., Truffer, M., Fahnestock, M., and Rysgaard, S.: On the seasonal freshwater stratification in the proximity of fast-flowing tidewater outlet glaciers in a sub-Arctic sill fjord, Journal of Geophysical Research: Oceans, 118, 1382–1395, https://doi.org/10.1002/jgrc.20134, 2013.

Munneke, P. K., Ligtenberg, S. R. M., van den Broeke, M. R., van Angelen, J. H., and Forster, R. R.: Explaining the presence of perennial liquid water bodies in the firn of the Greenland Ice Sheet, Geophysical Research Letters, 41, 476–483, https://doi.org/10.1002/2013GL058389, 2014.

Neteler, M., Bowman, M. H., Landa, M., and Metz, M.: GRASS GIS: a multi-purpose Open Source GIS, Environmental Modelling & Software, 31, 124–130, https://doi.org/10.1016/j.envsoft.2011.11.014, 2012.

Noël, B., van de Berg, W. J., Machguth, H., Lhermitte, S., Howat, I., Fettweis, X., and van den Broeke, M. R.: A daily, 1 km resolution data set of downscaled Greenland ice sheet surface mass balance (1958–2015), The Cryosphere, 10, 2361–2377, https://doi.org/10.5194/tc-10-2361-2016, http://dx.doi.org/10.5194/tc-10-2361-2016, 2016.

Noël, B., van de Berg, W. J., van Wessem, J. M., van Meijgaard, E., van As, D., Lenaerts, J. T. M., Lhermitte, S., Kuipers Munneke, P., Smeets, C. J. P. P., van Ulft, L. H., and et al.: Modelling the climate and surface mass balance of polar ice sheets using RACMO2 – Part 1: Greenland (1958–2016), The Cryosphere, 12, 811–831, https://doi.org/10.5194/tc-12-811-2018, http://dx.doi.org/10.5194/tc-12-811-2018, 2018.

Noël, B., van de Berg, W. J., Lhermitte, S., and van den Broeke, M. R.: Rapid ablation zone expansion amplifies north Greenland mass loss, Science Advances, 5, eaaw0123, https://doi.org/10.1126/sciadv.aaw0123, https://doi.org/10.1126/sciadv.aaw0123, 2019.

Oliphant, T. E.: A guide to NumPy, vol. 1, Trelgol Publishing USA, 2006.

Perner, K., Moros, M., Otterå, O. H., Blanz, T., Schneider, R. R., and Jansen, E.: An oceanic perspective on Greenland's recent freshwater discharge since 1850, Scientific Reports, 9, https://doi.org/10.1038/s41598-019-53723-z, http://dx.doi.org/10.1038/s41598-019-53723-z, 2019.

Pitcher, L. H., Smith, L. C., Gleason, C. J., and Yang, K.: CryoSheds: a GIS modeling framework for delineating land-ice watersheds for the Greenland Ice Sheet, GIScience & Remote Sensing, 53, 707–722, https://doi.org/10.1080/15481603.2016.1230084, http://dx.doi.org/10.1080/15481603.2016.1230084, 2016.

Porter, C., Morin, P., Howat, I., Noh, M.-J., Bates, B., Peterman, K., Keesey, S., Schlenk, M., Gardiner, J., Tomko, K., Willis, M., Kelleher, C., Cloutier, M., Husby, E., Foga, S., Nakamura, H., Platson, M., Wethington, Michael, J., Williamson, C., Bauer, G., Enos, J., Arnold, G., Kramer, W., Becker, P., Doshi, A., D'Souza, C., Cummens, P., Laurier, F., and Bojesen, M.: ArcticDEM, https://doi.org/10.7910/DVN/OHHUKH, date accessed: 2019-11-14, 2018.

PROJ contributors: PROJ coordinate transformation software library, Open Source Geospatial Foundation, https://proj4.org/, 2018.

Rennermalm, A. K., Smith, L. C., Chu, V. W., Box, J. E., Forester, R. R., van den Broeke, M. R., van As, D., and Moustafa, S. E.: Evidence of meltwater retention within the Greenland ice sheet, The Cryosphere, 7, 1433–1445, https://doi.org/10.5194/tc-7-1433-2013, 2013.

Rocklin, M.: Dask: Parallel Computation with Blocked algorithms and Task Scheduling, in: Proceedings of the 14th Python in Science Conference, edited by Huff, K. and Bergstra, J., pp. 130 – 136, 2015.

Sasgen, I., Wouters, B., Gardner, A. S., King, M. D., Tedesco, M., Landerer, F. W., Dahle, C., Save, H., and Fettweis, X.: Return to rapid ice loss in Greenland and record loss in 2019 detected by the GRACE-FO satellites, Communications Earth Environment, 1, https://doi.org/10.1038/s43247-020-0010-1, http://dx.doi.org/10.1038/s43247-020-0010-1, 2020.

Schulte, E., Davison, D., Dye, T., and Dominik, C.: A multi-language computing environment for literate programming and reproducible research, Journal of Statistical Software, 46, 1–24, 2012.

Schulzweida, U.: CDO User Guide, https://doi.org/10.5281/zenodo.3539275, https://doi.org/10.5281/zenodo.3539275, 2019.

Sergienko, O. V.: Glaciological twins: basally controlled subglacial and supraglacial lakes, Journal of Glaciology, 59, 3–8, https://doi.org/10.3189/2013JoG12J040, 2013.

Shreve, R. L.: Movement of water in glaciers, Journal of Glaciology, 11, 205–214, 1972.

Slater, D. A., Straneo, F., Felikson, D., Little, C. M., Goelzer, H., Fettweis, X., and Holte, J.: Estimating Greenland tidewater glacier retreat driven by submarine melting, The Cryosphere, 13, 2489–2509, https://doi.org/10.5194/tc-13-2489-2019, http://dx.doi.org/10.5194/tc-13-2489-2019, 2019.

Smith, L. C., Chu, V. W., Yang, K., Gleason, C. J., Pitcher, L. H., Rennermalm, A. K., Legleiter, C. J., Behar, A. E., Overstreet, B. T., Moustafa, S. E., Tedesco, M., Forster, R. R., LeWinter, A. L., Finnegan, D. C., Sheng, Y., and Balog, J.: Efficient meltwater drainage through supraglacial streams and rivers on the southwest Greenland ice sheet, Proceedings of the National Academy of Sciences, 112, 1001–1006, https://doi.org/10.1073/pnas.1413024112, 2015.

Stallman, R. M.: EMACS the extensible, customizable self-documenting display editor, Proceedings of the ACM SIGPLAN SIGOA symposium on Text manipulation -, https://doi.org/10.1145/800209.806466, 1981.

Stevens, L. A., Straneo, F., Das, S. B., Plueddemann, A. J., Kukulya, A. L., and Morlighem, M.: Linking glacially modified waters to catchment-scale subglacial discharge using autonomous underwater vehicle observations, The Cryosphere, 10, 417–432, https://doi.org/10.5194/tc-10-417-2016, 2016.

Stevens, L. A., Hewitt, I. J., Das, S. B., and Behn, M. D.: Relationship Between Greenland Ice Sheet Surface Speed and Modeled Effective Pressure, Journal of Geophysical Research: Earth Surface, 123, 2258–2278, https://doi.org/10.1029/2017jf004581, http://dx.doi.org/10.1029/2017JF004581, 2018.

Straneo, F., Curry, R. G., Sutherland, D. A., Hamilton, G. S., Cenedese, C., Våge, K., and Stearns, L. A.: Impact of fjord dynamics and glacial runoff on the circulation near Helheim Glacier, Nature Geoscience, 4, 322–327, https://doi.org/10.1038/NGEO1109, 2011.

Sugiyama, S., Sakakibara, D., Matsuno, S., Yamaguchi, S., Matoba, S., and Aoki, T.: Initial field observations on Qaanaaq ice cap, northwestern Greenland, Annals of Glaciology, 55, 25–33, https://doi.org/10.3189/2014aog66a102, http://dx.doi.org/10.3189/2014AoG66A102, 2014.

Tange, O.: GNU Parallel - The Command-Line Power Tool, ;login: The USENIX Magazine, 36, 42–47, https://doi.org/10.5281/zenodo.16303, http://www.gnu.org/s/parallel, 2011.

Tedstone, A., Bartholomew, I., Chandler, D., Cowton, C., Mair, D., Sole, A., Wadham, J., , and Nienow, P.: Proglacial discharge measurements, Leverett Glacier, south-west Greenland (2009-2012), https://doi.org/10.5285/17c400f1-ed6d-4d5a-a51f-aad9ee61ce3d, accessed 2020-02-21, 2017.

Trusel, L. D., Das, S. B., Osman, M. B., Evans, M. J., Smith, B. E., Fettweis, X., McConnell, J. R., Noël, B. P. Y., and van den Broeke, M. R.: Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming, Nature, 564, 104–108, https://doi.org/10.1038/s41586-018-0752-4, http://dx.doi.org/10.1038/s41586-018-0752-4, 2018.

van As, D., Hubbard, A., Hasholt, B., Mikkelsen, A. P. B., van den Broeke, M. R., and Fausto, R.: Large surface meltwater discharge from the Kangerlussuaq sector of the Greenland ice sheet during the record-warm year 2010 explained by detailed energy balance observations, The Cryosphere, 6, 199–209, https://doi.org/10.5194/tc-6-199-2012, 2012.

van As, D., Bech Mikkelsen, A., Holtegaard Nielsen, M., Box, J. E., Claesson Liljedahl, L., Lindbäck, K., Pitcher, L., and Hasholt, B.: Hypsometric amplification and routing moderation of Greenland ice sheet meltwater release, The Cryosphere, 11, 1371–1386, https://doi.org/10.5194/tc-11-1371-2017, http://dx.doi.org/10.5194/tc-11-1371-2017, 2017.

van As, D., Hasholt, B., Ahlstrøm, A. P., Box, J. E., Cappelen, J., Colgan, W., Fausto, R. S., Mernild, S. H., Mikkelsen, A. B., Noël, B. P. Y., Petersen, D., and van den Broeke, M. R.: Reconstructing Greenland Ice Sheet meltwater discharge through the Watson River (1949–2017), Arctic, Antarctic, and Alpine Research, https://doi.org/10.1080/15230430.2018.1433799, 2018.

Van Rossum, G. and Drake Jr, F. L.: Python reference manual, Centrum voor Wiskunde en Informatica Amsterdam, 1995.

Vandecrux, B., MacFerrin, M., Machguth, H., Colgan, W. T., van As, D., Heilig, A., Stevens, C. M., Charalampidis, C., Fausto, R. S., Morris, E. M., and et al.: Firn data compilation reveals widespread decrease of firn air content in western Greenland, The Cryosphere, 13, 845–859, https://doi.org/10.5194/tc-13-845-2019, http://dx.doi.org/10.5194/tc-13-845-2019, 2019.

Werder, M. A., Hewitt, I. J., Schoof, C. G., and Flowers, G. E.: Modeling channelized and distributed subglacial drainage in two dimensions, Journal of Geophysical Research, 118, 2140–2158, https://doi.org/10.1002/jgrf.20146, 2013.

Yang, K. and Smith, L. C.: Internally drained catchments dominate supraglacial hydrology of the southwest Greenland Ice Sheet, Journal of Geophysical Research: Earth Surface, 121, 1891–1910, https://doi.org/10.1002/2016jf003927, http://dx.doi.org/10.1002/2016JF003927, 2016.

Yang, K., Smith, L. C., Fettweis, X., Gleason, C. J., Lu, Y., and Li, M.: Surface meltwater runoff on the Greenland ice sheet estimated from remotely sensed supraglacial lake infilling rate, Remote Sensing of Environment, 234, 111 459, https://doi.org/10.1016/j.rse.2019.111459, http://dx.doi.org/10.1016/j.rse.2019.111459, 2019.

Zender, C. S.: Analysis of self-describing gridded geoscience data with netCDF Operators (NCO), Environmental Modelling & Software, 23, 1338–1342, https://doi.org/10.1016/j.envsoft.2008.03.004, https://doi.org/10.1016/j.envsoft.2008.03.004, 2008.

Zuo, Z. and Oerlemans, J.: Modelling albedo and specific balance of the Greenland ice sheet: calculations for the Søndre Strømfjord transect, Journal of Glaciology, 42, 305–317, https://doi.org/10.3189/s0022143000004160, http://dx.doi.org/10.3189/S0022143000004160, 1996.