We thank both reviewers for their diligence, and their many constructive comments.

Our response is structured as: our reply to reviewer 1, our reply to reviewer 2, and then our updated manuscript with changes highlighted.

Response to Referee 1.

We thank the referee for their thorough and positive review. In this document, the referee's comments are given in bold, and our response in normal text. Changes made to the manuscript are given in italics.

This is a comprehensive study that models seasonal ice surface velocities at a land- terminating glacier catchment in Greenland. The work pulls together other published component studies by the authors, including a model of supraglacial meltwater path- ways that drain through moulins into a subglacial hydrology model, which is coupled to an ice-flow model whose sliding parameters have been determined from an inversion using observed winter velocities. It is a challenging task to bring together many mod- elling and observational components and the results show some success. The paper raises many interesting points, including a comparison of results using the Weertman and Schoof sliding laws.

The differences between GPS velocities and modelled velocities highlight areas where future improvements can be made in model development. For example, it is interesting to see some similar challenges in Pimentel et al., Ann. Glac., 2017, e.g. difficulty in capturing early/pre-season speed-up and tendency in the model (with Schoof sliding law) for short-term speed-up events rather than more prolonged enhanced velocities.

In summary I do not have any major problems with the work and think it an interesting and valuable contribution that should be published. I list some minor issues and points of clarification that I would like to see addressed/corrected before final publication.

List of comments: Page 1

Title: The work is on one particular catchment of the Greenland Ice Sheet, rather than the entire Ice Sheet, this is not clear in the title.

Although we apply the model to Russell Glacier area, we believe the main contribution from this paper is broader. We show numerically that a multicomponent model including a distributed/channelized subglacial drainage component can be used to recreate ice velocities to a first order. This should be widely applicable beyond the study domain. However, we have amended the title to better reflect the nature of our study.

line 5: The acronym 'GrIS' is not defined

We use Greenland Ice Sheet here, and introduce the acronym in the first line of the introduction.

lines 8-10: Do we need further evidence to support that subglacial develop analogous to alpine glaciers and that models need distributed and channelized? This seems quite well established now in the field. Do you want this in the abstract as the key finding of this paper? At the very least 'support' and 'supports' should be changed to 'further support' and 'further supports'.

The evidence for distributed and channelized system of subglacial hydrology beneath the GrIS is mainly indirect: boreholes, dye tracing, and patterns of GPS measurements. However, no one has shown that this model can reproduce ice velocities (that we are aware of). We think this work uniquely supports it, in that we show numerically that this theory can begin to be applied to recreate and quantitatively predict velocity patterns (with the acknowledgement that there's a lot of work left). We modify the first 'support' to read 'numerically support'

line 11: ‘slow down’ of what?

We add 'of ice velocities'

line 16: The acronym ‘GrIS’ is not defined

Fixed

line 16: ‘margin’ should be land-terminating margin, because obviously marine terminating has other additional important influences.

We have expanded this sentence. While hydrological forcing is the primary driving force in land-terminating sectors, we do want the reader to have it in mind for marine-terminating sectors, since we suspect it is non-negligible there.

Surface meltwater draining into the subglacial system drives seasonal acceleration of ice velocities at land-terminating sectors of the Greenland Ice Sheet margin. It may also be a key factor for marine-terminating sectors (Howat et al., 2010; Sole et al., 2011; Moon et al., 2014)

Page 2

lines 12-13: Poor sentence, needs rewriting to make clearer.

Modified it to read:

As melt season intensity continues to increase, it remains unclear how ice velocities will be forced by water input at higher elevations where ice thickness is greater, and whether patterns of water input at higher elevations will change (Leeson et al., 2015; Poinar et al., 2015; Cooley and Christoffersen, 2017).

lines 21-23: Presumably just talking about GrIS here.

Yes, we think this follows from the last sentence, but we have added 'of the GrIS' to clarify.

line 30: typo “... to the drive the ...”

deleted the first 'the'

line 32: I’m not quite sure what you mean by “full spectrum of supraglacial drainage pathways”

We have modified the sentence to read:

However, no model including drainage via all of crevasses, moulins, and lake hydrofracture has been used to force a subglacial hydrology model to date.

line 34: How is it similar? You don’t seem to have components in the same sense as Arnold et al (1998) and Flowers & Clarke (2002)!?

We have components in the sense of including surface hydrology, subglacial hydrology, and ice dynamics. Although its true that our model setup isn't exactly the same, we think it's worth acknowledging these efforts which have tried to do something along the same lines in 2D.

Page 3

line 29: typo “... with with ...”

Fixed

line 30: A better reference is needed for context of Greenland melt intensity

Here we are highlighting the similarity of this to our previous work and have reworded the sentence to make this clearer:

Following Koziol(2017) , we use these three years as representative of summers with average, elevated, and extreme melt intensity respectively.

line 31: “. . . to determine crevasse locations . . .” How? Perhaps reference later section at end of sentence.

This is discussed later in the same section.

Page 4

Figure 1: typo “loactions”

Fixed

Page 5

line 5: “A threshold value of 145kPa is selected as optimal.” Optimal in the sense that it provided the best match to Landsat 8 image?

Yes, we think this follows from the previous sentence, but have reworded the sentence to make this clearer:

A threshold value of 145 kPa gave the best visual match.

line 10: “A small number of moulins . . .” could quantify percentage.

We didn't note the number when we processed the data set since it was only a very small number of moulins. We leave it as it is since we don't think there will be any benefit for the readers for us to determine it, given such moulins would drain negligible amounts of water as stated.

line 18 & 20: ? in citations

Fixed

line 21 & throughout: “surface to bed” “surface-to-bed”

updated

Page 6

line 6: “K_s” is “K” in equation (1) and table 1, so I think this should be “K” for hydraulic conductivity, whereas you have “K_s” to denote “sheet flux coefficient” in the table. However, this K_s does not appear in the text/equations! Hydraulic conductivity is given a value of 2 in the table, which does not match the description in the text!

Yes, this is clearly a mistake. K in Eq 1 should be K_s. K is deleted.

line 5-7: rho_w and p_w are not defined (rho_w is defined later on line 13).

Fixed.

line 19 & throughout: use \max and \min in latex

Fixed

line 19-20: N_0 a value is not provided in Table 1.

Fixed

Page 7

line 6: Presumably “R” is a rate and is a source term from the SRLF?

Exactly. We update the text to state that it is a rate.

line 10: You take the derivative of Eqn (9) wrt time as a term in Eqn (8). But is Eqn (9) constant!? Or is A_m a function of time?

A_m is constant. The numerators of Eqn (9) are p_w (water pressure), which is a function of time.

line 12: “The englacial storage parameter . . .” is this sigma – the “englacial void fraction”!?

Yes, this is an inconsistency. We have updated it to read englacial void fraction. We move P7L 11-18 to the start of section 3.2

lines 12-17: units are missing when giving values of conductivity. line 16: “khˆ2” should be capital K “Khˆ2”

Following on a previous answer, K→ K_s. Included units.

Page 9

line 7: “. . . a small regularization constant” – so this means the zero in N_+ = max(N,0), is not actually zero!? Is this constant different from “N_0” used earlier in equation (4)? What value do

you use for this regularization constant?

We've switched the notation here so that N_+ -> N_sl. We've amended the text to read:

and regularized with a small constant (10^2 \unit{Pa}).

line 16: "... weighted square of the difference of squares ..."!? This doesn't match equation (13) so I assume this should be square of the differences, rather than difference of squares!?

Yes, this is an error. We've updated the text.

line 19: please provide your chosen values for gamma_1 and gamma_2

Here we are discussing the model itself. We have added the following sentence to the beginning of the section workflow, P11L10:

(see Koziol and Arnold (2017) for details of inversions, which are done over the same study area but with a resolution of 500 m)

line 18-22: How was the weighting function chosen?

We update the last line of the paragraph to read:

The inverse of reported errors of surface velocities are used as weights.

line 18-22: U_obs(x,y) – are these just the 7 GPS sites? So the weighting function is 1 at these locations and zero elsewhere!? Ok, I just checked back to Section 2.1, so U_obs is the winter mean from MEaSURE. And the weights are from the provided error estimates from MEaSURE!?

Exactly. P11L5 states 'All linear inversions are run using mean winter velocities from 2009...' Here we are focused on describing the model.

line 18-22: Why isn't "U_s" also written "U_s(x,y)"?

Updated.

line 18-22: It would be clearer if you explicitly said that U_s is a function of \alpha and

you seek to minimize J with respect to \alpha. If I have understood correctly?

We never explicitly define what an inversion is in this section, since we figured they are fairly standard in glaciology. However, we modify the text to be more explicit:

The inverse of reported errors of surface velocities are used as weights. Modelled surface velocities depend on the control parameter via the sliding law. The inversion procedure minimizes the cost function with respect to the control parameter.

line 24: An odd/abrupt start to this subsection

We have changed the first sentence to read:

The SRLF model is used to determine supraglacial input rates to the subglacial system.

line 25: There is englacial storage in the subglacial model, but water from the SRLF is not directed to this storage – correct!?

Yes, we have modified this to read:

For model integration, we assume that water drainage through surface-to-bed connections is strictly vertical, with no horizontal component.

line 27 "All water entering these cells drains directly to the bed" So water is not stored in the moulins – how does this relate to Eqn (9)!?

This was imprecise. There is water storage in moulins. We think this new sentence better communicates our point:

All water entering these cells drains into the subglacial hydrology system at that location.

line 29: ". . . the water is removed from the model . . ." do you actually mean the water vanishes!? Because on page 10 line 2 you say ". . . all water in crevasse fields drain to bed . . .". If I understand correctly the water in the crevassed grid cells ends up draining into a nearby moulin where it then enters the bed.

The SRLF model is strictly a surface hydrology model. When water enters a cell with a surface to bed connection, it is removed from the model. Since it's no longer on the surface, no further routing needs to occur. We then have to postprocess these results to provide input to the subglacial hydrology model. For moulins/lake hydrofracture, we can put the water into the subglacial system at the same location. Since not every crevasse cell will drain locally to the bed, these require more involved post-processing.

Thus, we have removed the clause ". . . the water is removed from the model . . .", which we think should avoid this confusion.

line 29: ". . . and no further routing occurs." It is instantly routed to the corresponding moulin – if I understand your next paragraph correctly!?

No further routing occurs in the SRLF model. We have to postprocess the results and implement the routing after the SRLF model run. We rearrange the sentence slightly to be clearer.

When water enters a crevassed cell in the SRLF model, no further routing occurs.

Page 10

line 11: "veronoi" "Veronoi"

Fixed

Figure 3: It may be helpful to somehow illustrate the crevasses (crevasse field). You could possibly use hatched grid cells, like in Figure 6. I suppose this is implemented in a finite difference grid, so the curved lines of the internal catchment would actually be straight edged.

We have shaded the area within the crevasse field, and added a corresponding line in the caption. Hatched lines are not a default option in the open source graphics editor we are using (Inkscape). In a finite difference scheme any curved line is made up of small segments of straight lines, we think this is a negligible detail. A schematic drawing implies that the elements are representative rather than realistic.

Page 11

line 8: "The effective pressures at the end of the . . . simulation . . ." Presumably they've stabilized by then?

Yes, we see a large initial transient response in the first 50 days or so. We have added a line stating that they reach an approximate steady state by the end of the winter run.

line 10: "coefficients." State the coefficients, i.e. "coefficients, mu_a and mu_b."

Updated

line 10: "... the basal water pressures, ... form inputs ..." how are the basal water pressures used? Initial conditions of the subglacial summer simulations!?

We have modified the next sentence to read:

The integrated model is then run for the summer melt season ***using the end of winter effective pressures as an initial condition.***

line 16: "A parameter search . . .". I'm not sure what you are getting at with this sentence.

We have modified this sentence to read:

A parameter search therefore requires performing the inversion using an effective pressure dependent sliding law for each set of parameters tested.

The implication here is that it is costly.

line 18: ". . . sensitivity analysis (not shown)." Section 3.3!?

We have removed this clause as both reviewers commented on it. What we meant for this to communicate is we don't show each of the nearly 200 sensitivity runs, but rather the final calibrated runs.

Page 12

Section 3.1: What percentage of your lakes hydrofracture? I don't think you provide this value, but you should. How does it compare to observations, in particular the recent study by Cooley &

Christoffersen (2017) could be relevant to determine if this is consistent with observations?

We have amended the text as:

Approximately 12\% of supraglacial lakes are predicted to hydrofracture. These events drain only a small percentage of surface runoff (1.3\%).

There are comparisons of the SRLF model results to satellite imagery in Arnold et al. 2015, as well as Koziol et al., 2017. In the latter, we refine the calibration so that ~11% of lakes hydrofracture, and ~38% of lakes drain via channel incision. Although the calibration is for the Paakitsoq region (just north of Jakobshavn Isbrae), the numbers we calibrate to are for SW Greenland, and we expect it to be valid in our present study domain.

Figure 5: This is a very poor figure and needs changing or removing. In the words of John Turkey: "There is no data that can be displayed in a pie chart, that cannot be displayed better in some other type of chart."

We have replaced it with a table.

Page 13

Figure 6: I think a different colour scale would be better. The colours for moulin, crevasse and lake hydrofracture need to stand out from the background colour scale, as do the hatch marks which also get a bit lost. If I understand correctly the total area of the red circles should be ~double that of the blue circles (based on fig 5), which appears to be the case. Can you also include the GPS sites on this figure? I'm interested to see how close the sites are to the supraglacial input locations.

We put a lot of effort into making this image; the colour scale is the best we found. The hatchmarks are difficult to modify, as it's quite a hack in Matlab to get them to appear. Overall, we think the appearance of the figure is satisfactory, but we have included GPS positions as black triangles as suggested by the reviewer, and updated the caption.

Section 3.2: What exactly are you calibrating in the model – which parameters are being varied to best match the duration and magnitude of speedup events? The results shown in this section are the end result after the calibration (e.g. fig 7 & 8)!? But then that is no different from the 2012 results in section 3.3 (e.g. fig 9)!?

We move P7L 11-18 to the start of section 3, and add clarify by adding:

The focus of the calibration is on parameters identified as key to determining the morphology of the subglacial system, K_s and σ.

line 11 & elsewhere: "RACMO2" or "RACMO2.3" (from page 3 line 26)

Updated to RACMO2.3 throughout

Page 14

Figure 7: could label on which of the automatic weather stations is displayed (e.g. AWS5 is shown in (b) etc.). The same for Fig 8 & 9.

Updated

Page 16
line 24 & elsewhere: It is standard to separate out multiple units using $\,$ in latex,

e.g. $\mathrm{m}\,\mathrm{yr}^{-1}$.

Updated

Page 17
line 7-8: “In this section, . . .” This sentence is poor and needs restructuring.

Rewrote as:

In this section we focus on the sensitivity of the model to the setup, to K_s, and to σ.

line 16-17: “The impact . . . where the water . . . was not input to the base.” Where was the water put instead? Removed? Drained to the bed less suddenly!? Your sentence appears incomplete, or another sentence to explain is needed.

We have amended the sentence by adding the clause *', but removed from the system.'* to the end of the sentence.

line 18: “The impact . . . was negligible.” This surprises me. So velocities at the drainage locations (or just downstream) are unaffected by rapid water input!? Or are you just referring to velocities at the GPS sites (which may not be close to the drainage input locations)?

We amend the sentence to state we are referring to the GPS stations.

line 20: “... calibration runs, ...” here I take “calibration runs” to mean the baseline runs after calibration (i.e. Figs 7 & 8).

We change 'calibration' to 'calibrated', which should be a lot clearer.

Page 18

line 6-7: “... elevated velocities ...” I don’t see this in figure 9(a) – two slight blips perhaps!?

Yes, this is hard to see. We update the text to say ...'slightly elevated velocities…' The model clearly gets the magnitude wrong, however the timing is there.

line 24-25: “. . . dependent on melt input.” But there appears to be no or little surface runoff at this time (day 238-242)!?

Plotting mistake. – the background melt in the figure is for 2012, not for 2011. We have updated this figure.

Page 21

Figure 11: Vertical axis should say "velocity". The figure may be better if the horizontal axis had a scale as well, e.g. distance from terminus/ice-margin or elevation. Could you also have a vertical dashed line on the graph indicating the equilibrium line.

Updated vertical and horizontal axis. We now show an elevation profile in this figure as well. We decided the figure looked better without the vertical line indicating the equilibrium line.

line 12: "qualitatively" presumably the maximum extent of channelization can be quantified.

Yes, we have the data, but the files are cumbersome to work with, and we don't feel there is a significant benefit from quantitatively performing the analysis.

line 16-22: What year where the tracers injected?

We amend the paragraph to say:

Dye-tracing experiments by \citet{Chandler2013} were performed in the summers of 2009 to 2011.

and

Based on tracer measurements ***in 2011***

Page 23

Figure 13: Are the 3 red dots all L1? These moulin injection sites do not appear to be moulin locations in your model!? I'm comparing to Figure 6!?

Only the closest dot to the margin is L1. We amend the caption to say:

Two moulin locations are unlabeled for clarity.

Comparing Fig 13 to Fig 6, we agree that L1 does not appear. It may be a crevassed cell though. The first unlabeled site (closer to the margin) would be one of the crevasse cells. Note when our crevasse prediction overlapped with a moulin observation, the moulin was deleted, as it would not receive any water in the model. The second unlabeled injection site (further from the margin), appears in Fig 6. IS39 and L41 have moulins nearby in Fig 6, and L57 does not appear – although there are moulins upstream. There is some discrepancy as observed moulin locations are from 2014, and moulin locations from Chandler et al (2013) are from 2009-2011.

Page 24

lines 1-2: ". . . there is a brief period . . ." Is there? Is this right at the end, after day 250? It's hardly worth mentioning is it!?

We modify the sentence to be more specific that we are referring to 2011 and 2012.

Figure 14: A sheet-dominated to channel-dominated drainage “switch” seems only to occur with the 2011x4 results. This is a significant difference with the other simulations and worth discussing in the text. Although, the “switch” does not seem to noticeably effect the ice velocities.

We have expanded the discussion of this within the text.

Page 25

line 3: typo “computational imposed limitations” computationally!?

Updated

line 3: typo “... choice ice sheet ...” “... choice of ice sheet ...”

Updated

lines 9-10: “. . . likely to lead to stresses assumed negligible . . .” needs rewording

We have simplified the whole sentence to:

Steep surface gradients may lead to stresses assumed negligible by the hybrid formulation in the ice stress balance.

line 13-14: “The atmospheric pressure . . .” I’m not sure what exactly you mean by this sentence can you explain further. Is this something that can be easily checked?

Reworded as:

The atmospheric pressure boundary condition prescribed at the ice sheet margin in the subglacial hydrology model, …

This is not something easily checked. However, observations of R-channels exiting glaciers show that they are not always full. We believe it is a reasonable assumption that this could extend some way away from the ice margin, and that these channels could oscillate from partially full (or unpressurized) to full. The model assumes these channels are always full (pressurized).

line 15: units

We don't see any numbers on this line, this might belong on the next page where we missed units.
line 15: typo “Similarly to the study . . .” “Similar to the study . . .”

Updated

Page 26

line 16: “The parameter values . . . in Banwell . . .” state their values to help comparison.

We have reworded the section as follows to be more clear:

Most model parameters of the integrated model are similar to previous studies applying the subglacial hydrology model (Hewitt, 2013; Banwell et al., 2016). The most significant parameter value difference *is the sheet flux coefficient (Ks). The primary value of 10−2 Pa−1s−1 in our study is greater than the value of 10−5 Pa−1s−1 used in Banwell et al. (2016). The parameter values for the model reported in Banwell et al. (2016),...*

lines 27-28: "The initial rapid delivery . . . of water to the bed . . . are not observed to have an effect in [on!?] modelled velocities." Is this just at the GPS sites or everywhere, even close to the drainage locations!?

We have re-worded this sentence to make it clearer that we are discussing the broader impact on ice velocity, rather than any short-term, localised effect.

The initial rapid delivery of a large volume of water to the bed during individual lake hydrofracture events is not observed to have a lasting or widespread effect on modelled velocities.

Page 27

line 6: ". . . a good match . . ." good might be too strong, perhaps "reasonable".

Updated

line 11: "higher order" "higher-order"

updated

line 29: ". . . in line with observations by Hoffman . . ." in line with "findings"!?

Their work is based on GPS measurements, so we think 'observations' is the correct word to use.

Page 29

line 24: "GriS" "GrIS"

Updated

Page 33

line 31: "Proceedings of a workshop held at Seattle . . ." seems vague, I'm not sure how the journal will view this type of reference.

We update the reference to:
Raymond, C. and Nolan, M.: Drainage of a glacial lake through an ice spillway, Intl. Assoc. Hydrol. Sci. Publ., 264, 199–210, http://iahs. info/uploads/dms/iahs_264_0199.pdf, 2000.

which is how it was cited in our Journal of Glaciology paper (Koziol et al., (2017)). This paper has been cited in Kingslake et al. (2015, JGlac), and Jarosch and Gudmusson (2012, TC) as well.

Response to Referee 2.

We thank the referee for their thorough review. We accept that certain aspects of the text could be re-worded with a different emphasis to better reflect our findings and their implications. In this document, the referee's comments are given in bold, and our response in normal text. Changes made to the manuscript are given in italics.

This study couples together a surface drainage, ice flow and subglacial hydrology model to examine ice dynamics in the Russell Glacier catchment in Greenland. It's nice to see efforts to couple models like these together as, on their own, it is difficult to fully understand the system. Also, this is a good location to apply this type of study since I think more in situ data has been gathered here than anywhere else in Green- land. In particular, I thought the scenarios of increased melt input were helpful for assessing the dynamic impacts of basal hydrology. The authors argue that the primary output from their model is a confirmation of the hypothesis for an 'Alpine'-like drainage network at the margin of the Greenland Ice Sheet where an initial summer speed-up is followed by deceleration as efficient channel networks develop.

There was a thorough discussion in the paper about the different aspects of the model C1 and the tests that have been carried out. However, improvements can be made, par- ticularly in the very strong support of the 'Alpine' drainage model, which is really only applicable to the very margin, while the model covers areas much further inland. Also I caution the authors against support of hypotheses applied to the whole of Greenland when Russell Glacier is a fairly slow-moving land-terminating glacier, unlike many of the regions where much of the mass loss is occurring by calving processes at tidewater glaciers. On the whole, I think this paper would be improved by toning down and clarifying some of the arguments as I detail below.

Major points:

The overwhelming argument in the paper is that water gets to the bed in the spring, grows channels and that causes ice deceleration. This is reported as the 'Alpine' model of drainage and, indeed, both the GPS data and the model outputs from this study support that, where the Greenland ice sheet is similar to an Alpine glacier (i.e. near the margin where lots of water gets to the bed and, most importantly, surface slopes are steeper), it does act similar to an Alpine system. However, when you go further inland, both the GPS data and the model in this paper support the argument that has been made in other papers (e.g. Meierbachtol et al, 2013, Andrews et al., 2014, Dow et al, 2015, none of which, by the way, were cited or discussed), that the shallow surface slope prevents large, efficient channels from forming and therefore more water input means higher velocity. This is not the Alpine drainage model. I strongly argue that the authors should recognize that their model outputs show this. The authors do discuss this inland acceleration within the main text but it is not mentioned in either the abstract or conclusion. This acceleration, particularly in the cases of increased melt input, is one of the more important outcomes of the modeling exercise and should therefore be highlighted.

We think the article communicates a broader point. The main contribution from our perspective lays with showing that a multicomponent model incorporating both distributed and channelized systems of subglacial hydrology can be used to recreate GPS velocities to a first order. There is indirect evidence for the existence of a distributed/channelized system beneath the GrIS from observation of boreholes, dye tracing, and the GPS velocity patterns, but to date, no model has been developed including all these elements which is able to recreate surface velocity measurements. The model we develop in this paper provides numerical support for this understanding of subglacial hydrology beneath the GrIS, as well support for the explicit description of the model components (i.e. the equations used). Since the model works to a first order, we also aimed to investigate what ice velocities may look like in the future through a series of simple tests. The model predicts that ice velocities will scale with summer melt input (which we state in the abstract and conclusion via 'strong summer velocity scaling').

The quantity of interest in order to understand possible dynamic changes affecting ice sheet mass balance is annual average ice velocities, rather than summer average velocities. Since we do not model winter velocities, to make this link, we rely on trends observed in GPS velocities. Previous literature shows that in the upper ablation zone of the Russell Glacier Area, there is an inverse relationship between summer velocity and annual velocity (e.g. Figure 7, Van de Wal et al., 2015). As melt input increases, annual velocities decrease at a faster rate than average summer velocities increase. This is explained to be due to the effect of channelization on winter velocities (an argument made by others, including Sole et al. 2013). Our model predicts both faster summer velocities, and increased rates of channelization for higher melt scenarios. Hence, we make the assumption that current observed trends will continue, and investigate the limit of this behaviour, which is when winter velocities will hit their lower bound. Although the assumption we make is not constrained by our model output, and has uncertainty in it due to the points raised by the reviewer, we think it is quite reasonable.

It is evident from the equations that thick ice and shallow slopes inhibit channel growth. However, it is not clear to us that our system shows a limit where increased water input results in increased annual ice velocities, as we do not model winter ice flow. However, we now include this discussion, and the references mentioned. In particular, we also discuss the model implications in the limit of summer velocities increasing but winter velocities remaining constant.

Most of the understanding of subglacial hydrology we have comes from alpine glaciers. This includes the concepts of distributed and channelized systems, as well as the equations. An alpine drainage system encompasses these elements, and the term has been widely used in the literature when discussing the behaviour of the Greenland Ice Sheet.

In order to better emphasize the points raised above and also to reflect the reviewer's comments, we have made the following changes.

We better highlight the link between average summer ice velocities and melt season intensity in the abstract.

P1 L11-14 (Abstract)

This suggests current trends of decadal timescale slow-down of ice velocities in the ablation zone may continue in the near future. The model results also show a strong scaling between average summer velocities and melt season intensity, particularly in the upper ablation area. Assuming winter velocities are not impacted by channelization, our model suggests an upper bound of a 25% increase in annual surface velocities as surface melt increases to 4x present levels.

We delete this sentence.

P28 L18. ~~*The model results also support the hypothesis that the margin of the GrIS is controlled by*~~

~~subglacial hydrology in a manner similar to alpine glaciers.~~

We then move lines P28 L12-17 to the end of the section (P29 L23), and insert this paragraph in its place.

The existence of channelized and distributed systems beneath the GrIS is inferred indirectly through borehole observations, dye tracing experiments, and patterns of GPS velocities, building on extensive observations and theoretical developments derived from studies on alpine glaciers. The key result of this paper is to provide numerical support for the understanding of subglacial hydrology of the GrIS, based on theories derived from studies of alpine glaciers, as well support for the explicit description of the model components we include (i.e. the equations used). We show that these theories can quantitatively reproduce measurements to a first order, and in the sense of our validation, predict ice velocities. This builds on previous work which shows that this understanding can be used to reproduce idealized seasonal patterns of ice velocity \citep(Pimentel2011, Colgan2012, Hewitt2013), as well as effective pressures in line with ice velocities \citep{Werder2013,Fleurian2016}.

We have also expanded the discussion on P29 of velocity sensitivity to melt considerably.

However, as channelization increases up-ice in our model, we do not see a marked impact on model velocities. Model velocities at the higher GPS stations in model runs 2011x2 and 2011x4 both show a similar pattern to 2011, with a higher magnitude of ice flow during speedup events. We do not observe a shift in velocity patterns towards that of lower GPS stations, with acceleration early in the melt season transitioning to deceleration in the latter part of the melt season. This suggests that channelization may have a more limited impact on annual velocities in the accumulation zone. The magnitude of any impact is unresolved by our model. In particular, although there are periods when velocities in the 2011x4 run are lower than 2011x2 and 2011, the magnitude of this decrease is bounded. This is a limitation of the model, which is only able to decrease velocities nominally below the initial winter values. This also has the consequence that we are unable to model the winter season accurately.

The key question for the longer term response of the ice sheet to increased melt is whether the potential summer increase in velocity due to increased melt will outweigh any late summer and winter decrease due to the evolution of a more efficient system under higher melt conditions. While observations show long-term decreases in ice velocities in the lower ablation zone \citep{Stevens2016, Tedstone2015, VandeWal2015}, this question remains unresolved at higher elevations. Although we cannot directly predict annual velocities with the model presented in this study, we can investigate how annual velocities may change at the limits of winter behaviour.

One limit of winter velocities is that integrated ice flow over the winter decreases faster than integrated ice flow over the summer. This is observed in GPS measurements in the upper ablation zone in the Russell Glacier region by \citet{VandeWal2015}. Under this limit, channelization has a similar impact at high elevations as in the ablation zone. Velocity measurements near the vicinity of a lake hydrofracture at approximately 1450 \unit{m} elevation suggest that channelization occurs even at high elevations \citep{Bartholomew2012, Nienow2017}. Winter velocities in this limit will decrease until they hit a lower bound where flow is purely deformational, with no contribution from basal *sliding. The maximum increase in mean summer velocities is approximately 60 \unit{m yr^{-1}}, at GPS stations 4 and 5 between the 2009 and 2011x4 melt scenarios. Assuming a winter velocity of 100 \unit{m yr^{-1}} and an 7 month-long winter, the summer increase predicted by the model would compensate for a possible reduction in winter velocity to around 60 \unit{m yr^{-1}}. This approaches the lower bound for winter velocity suggested by borehole measurements showing that internal deformation accounts for 25-50\% of the total ice velocity in the Paakitsoq region of western Greenland \citep{Ryser2014}. Climate model predictions suggest surface runoff rates quadrupling from present levels circa 2100 \citep{Shannon2013, VanAngelen2013}.*

The second limit occurs if winter velocities at higher elevations are not impacted by channelization, and summer velocities dominate the annual signal. Arguments that thick ice and shallow surface slopes inhibit channel growth at high elevations favour this limit of behaviour \citep{Meierbachtol2013,Dow2014}, as do observations suggesting limited changes in the efficiency of the channelized system \citep{Andrews2014}. Under this scenario, a change of mean summer velocity of 110 \unit{m yr^{-1}} to 170 \unit{m yr^{-1}} with winter velocities remaining constant at 100 \unit{m yr^{-1}} would result in mean annual velocities increasing from 104 \unit{m yr^{-1}} to 129 \unit{m yr^{-1}} between the 2009 and 2011x4 simulations. Under this scenario, annual velocities would increase by approximately 25\% by approximately 2100, when surface runoff is predicted to quadruple.

Similarly, the role of channels in the drainage system is something that should be more carefully discussed by the authors. While subglacial channels can grow at high elevations under the Greenland Ice Sheet, it doesn't really matter until they start poaching water from the distributed system and therefore increase the system effective pressure i.e. presence of channels does not equal efficiency. Unless the surface slopes of the interior steepen considerable, there is no mechanism to efficiently remove water as the hydraulic gradient in channels will not be steep enough and therefore more water will mean faster velocities. So on page 21 where you report channels growing up to 50 km from the margin, that's fine, but these don't appear to be having much impact on the velocity, which is what you're interested in. That should be pointed out and the arguments that more channels inland will mean a velocity decrease, rephrased.

On P21, we are simply discussing the results of the model, not their implications. However, we accept the arguments raised by the referee here, and we have modified some aspects of the discussion and conclusions to reflect this, as discussed in our response to the general comments. Also, we already discuss the idea that the overall scaling of velocity with increasing melt suggests that the growth of channels does not cause a velocity decrease when viewed at the scale of the whole model domain.

I think the authors need to less strongly argue that the model outputs fit the GPS velocity data well. For example on PG24 13-14 it is stated: 'many of the features observed in the GPS. . .are captured in the modeled velocities'. On many of the plots in Figures 7 and 8, the GPS velocity is slowing down while the model is speeding up (e.g. 2011 Site 4 day ~203; 2011 site 5 day ~195), and there are few places where I think the model and the GPS would have a good correlation on a day-to-day basis. This doesn't mean that the model outputs aren't useful and I'm not expecting the authors to do any more model runs. However, merely to be more careful with their language. For example, the authors could say: a reasonable fit between seasonal patterns from GPS

velocities and modeled velocities.

We have tried, where appropriate, to be more careful when describing the level of agreement between the model results and observed velocity. In particularly in Sections 3.2 and 3.4 we are careful to discuss both areas of agreement between the model and observations, but also areas of mis-match.

Line-by-line comments:
PG1
1: can you specify what you mean by margin. How far inland does that go? This doesn't necessarily have to be in the abstract but should be noted somewhere in the main text.

'Margin' isn't meant as a technical term, and has been used in its general English meaning of the edge or border, in line with other papers in the literature.

1-2: The first line of the abstract is misleading since you then immediately say that meltwater also leads to deceleration.

We state ice flows faster during the summer. The pattern of ice flow shows acceleration early in the summer ($du/dt > 0$), and deceleration in the latter part of the summer ($du/dt < 0$). These are not contradictory. Ice velocities can be decelerating, and still have a greater magnitude than during the winter.

PG2
8: where are these measurements?. . .accumulation or ablation zone? This is confusing following on from the previous sentence.

Updated to 'in the ablation zone'

13: references needed at the end of this sentence e.g. Leeson et al, 2015
Added references to Leeson et al., 2015, Poinar et al., 2015, and Cooley and Christofferson, 2017

23: what do you mean by 'recent hydrological models'?
Recent hydrological models are defined on lines PG2 L14-16, and are those that incorporate both distributed and channelized system, as well as explicitly treating the interaction between the two. On line 16, we also give a list of references to these models.

24: what feedback?
There is a feedback between velocity and the distributed system as water pressures impact ice velocities, and ice velocities impact water pressures (e.g via cavity opening/closing or till deformation).

We have removed 'an' to reduce the emphasis on this particular feedback.
25: 'comparison to ice surface velocity measurements'
changed

27: 'coupled ice dynamics/hydrology models'
changed

29 (and 31): what do you mean by 'necessary elements'? In the context of modeling this is

confusing since some of the models you discuss include finite element grids.
By elements, we refer to parts like channels or linked cavities. Flowers (2015) also uses this terminology. It would not make sense to ask '(whether) models presently include the necessary elements' in reference to FEM.

30: to drive the subglacial hydrology model?
changed

31-31: repetition of 'different'
Deleted the first instance.

32: 'no model to date has included the full spectrum'. This suggests that you do include the full spectrum. From your description of the surface hydrology model it doesn't seem to me like there is anything different from the previous applications of this model. If you have adapted it, you should specify the main changes and why you think this represents the full spectrum.

This version of the surface hydrology model has only been used once before (Koziol et al., 2017). In this version, drainage through crevasses, moulins, and lake hydrofracture are represented, which we believe represents the full spectrum of drainage paths from the surface. The model is different from the version used in Arnold et al (2014), Banwell et al (2012), Banwell (2016), which only allowed lake hydrofracture and moulins at the bottom of lake depressions. Crevasses and moulins outside of lake basins were neglected.

However, to also take into account both reviewer's comments, we have modified the sentence to read: *However, no model including all of crevasses, moulins, and lake hydrofracture has to date been used to force a subglacial hydrology model.*

PG3
1: 'This coupled model. . .'
Updated

18+20: repetition of 90 m resolution topography usage
We remove subsequent references to 90m

31: can you specify which boundary conditions you are referring to here.
It's used to determine both subglacial water pressures, and the coefficients of the sliding law, within the workflow described later. For clarity, we think its simplest to leave it as it is here, but we refer forward to Section 2.6 which discusses this in more detail.

PG 5
3: why the assumption of -5 degrees C?
We tried a few different values when we came up with the crevasse map, this worked reasonably and seemed plausible given the polythermal nature of the ice sheet and the fact that we tune the threshold stress to best fit the observed crevasse locations.

4: which Landsat8 image?
We have added the date: 19 August 2013.

14: repetition of 'in'

Fixed

16: the first sentence is repetition of the 90m resolution for the third time
We keep this in case the readers skipped the study area/data set section

18: missing reference
Fixed

20: define what you mean by a fracture area criterion. Also is this fast-drainage dataset driven by that fracture criterion checked against the satellite imagery record of lake drainages?

The idea of a fracture area criterion to predict lake drainage is widespread in the literature, and we have referenced our previous study which forms the basis of the supraglacial model we use here at the beginning of this paragraph. To re-define this here seems unnecessary. Comparison of the hydro-fracture predictions against satellite imagery have been made in Arnold et al., (2015). The method has been shown to reproduce the observed timing of lake hydrofracture (as a function of elevation), but not predict the fate of individual lakes. The model is further calibrated to predict observed numbers of lakes hydrofracturing/draining over the ice surface via channel incision in Southwest Greenland (Koziol et al., 2017).

PG6
1: is that basal no flux condition accurate? Particularly on your upper boundary I would expect some basal water flux into your domain.

We would expect some lateral flux in the subglacial hydrology system at the margins. However, the no-flux boundary condition is the most sensible one to prescribe in this model. Figure 1 shows that the surface gradient is mainly parallel to the long axis of the domain, and we did our best to align the margins with the edges of subglacial catchments calculated using the Shreve potential. The GPS stations are also 20km away from the margin, which should mitigate many of the effects on ice velocities. In terms of input of basal water across the up-glacier boundary, we would expect this to be limited, and the simplest approach seemed to again assign a no-flow boundary condition. The bed may be frozen near this boundary.

6: Ks here but K in Eq1
Fixed

10: Eq2 – what is h_cav?
We change h_c to h_cav on line 9.

11 (and 16): U_b is the basal sliding speed but u_b is the basal velocity? What is the difference?
Speed is a scalar, velocity is a vector.

16: how do you calculate basal drag? Also for u_b what is b in the (x,y,b) dimensions? You should also specify what v is.

An explanation of how we calculate velocities and basal drag is in the following section (Ice Flow/Inversion). This includes Eq 10-12 which clearly detail how basal drag is calculated. For the purpose of detailing the subglacial hydrology model, it's simplest to assume t_b and u are given.

We have modified line on 8 to include the definition of b(x,y) as the bed. \bold{u} denotes a vector, and u and v are the components..

PG7
3: what do you mean by incipient channel width?
We have amended the text with an explanation

where λ_c is an incipient channel width lengthscale (melting of basal ice over this scale contributes to channel initialization).

5: what is x_c? If this is along-channel distance, what is the difference between this and r?

x_c/x_m are the positions of the channels. Their use in this equation communicates that channels/moulins are discrete entities (not a continuum like the distributed system).

11-14: How did you choose the % of cells to change and the value to change them to? Did you sensitivity test this? For this whole paragraph you need to include units.

We've updated the text to include units. This was extensively tested, and we've moved P7 L11-18 to the start of section 3.2 to reflect this. We also add:

The focus of the calibration is on parameters identified as key to determining the morphology of the subglacial system, K_s and σ.

16: what is k?
This was a typo, and is updated to read K_s.

PG9
6: Perhaps the removal of negative effective pressure is why you aren't replicating the higher upstream GPS velocities.

Negative effective pressures are removed for calculating basal drag, not from the system. Using negative effective pressures in these sliding laws results in unphysical effects. Intuitively, basal drag is zero once ice is floating.

PG10
3: unclear what you mean by an internal water table. References needed here.

This reflects the assumption we make that all crevasses within a contiguous crevasse field are hydrologically connected; the idea of an 'internal water table' attempts to provide a picture for the 'leakage' or 'sharing' of water between the individual crevasses in a crevasse field, rather than having a precise definition, but we have removed this clause to leave the assumption as just that.

PG11
18: why do you say 'not shown' for the sensitivity analysis? What about section 3.3?

We have removed this clause as both reviewers commented on it. What we meant for this to communicate is we don't show each of the sensitivity runs, but rather the final calibrated runs.

PG12
10-12: I don't understand the sentence beginning 'Water routing...'. L10 say 70% routed into crevasses, L11 says 50%.

We wanted L11 to communicate 50% of that 70%. We have modified the lines to read:

Water routing into crevasses is concentrated in a small number of cells, with 50\% of the water routed into crevasses entering in only 100 of the 7573 cells forming the perimeter of crevasse fields.

PG13
3-4: I find it confusing that the surface input is not varied. What do you mean by this?

We mean that we only use one surface runoff time series of RACMO2.3 for each year. In reality, this time series will have some errors associated with it, and there will be a number of plausible times series within this error range.

Thus, we change this sentence to make this clearer:
The calibration focused on matching the duration and magnitude of speedup events, as the timing of the events is controlled by surface input, which was not sensitivity tested, given we used the same time series of surface runoff for each year from RACMO2.3 in all SRLF runs.

5: which plots?

This refers to Fig 7 and 8.

7: are you saying because sub-daily variability is subdued, you've averaged to daily? Otherwise this doesn't make sense following the previous sentence.

To compare against the daily average GPS speed, we need to calculate daily average (or approximate the daily average) modelled velocities. Here we are stating that for the Weertman Sliding Law (Note in the text we have switched from Weertman to Budd to be in line with reviewers' suggestions for our previous publication Koziol and Arnold (2017)), we use the model output from noon as representative of the daily mean (added to the sentence). For the Schoof Sliding Law, we output velocities every six hours and use those to calculate the daily mean as stated. This works for the Weertman sliding law since sub-daily variability is subdued. The only time we really see high sub-daily variability is when the Schoof sliding law predicts high velocities. We try to minimize the number of times we save the state of the model, as these files are large.

9: which model output?

This applies to model velocities, but as well as to the values in our supplementary videos. This is a generic statement saying that whether you run the coupled model for one summer, or run it for summer + winter + summer the results are the same. We have removed 'all' from this sentence to make this clearer.

PG 14

3-5: I'm afraid it doesn't look like a good fit to me at all. There's a lot of variability in the GPS that aren't captured in your model outputs and events in the model that doesn't appear at all in the GPS. I think you have to have to be much more upfront about these poor fits.

We do not claim a good fit here, but a 'comparable' fit for the two modelled sliding laws. In the remainder of this section we describe the model fit for different GPS stakes and over the season quite carefully, highlighting areas/times when the fit is good, and other times when the model differs from observations. We have gone through the paper carefully to ensure that we do not over-state the degree of fit. The phrase we often use is 'to a first order'. We agree that 2009 is not a great fit, 2011 and 2012 are better.

PG16
3: how near the ice sheet margin?

We update the sentence to read:

The model predicts low ice velocities throughout most of the summer melt season at the three GPS sites closest to the margin.

4: low velocities through the summer melt season? Why is there no spring event at the beginning? This is a key of the 'Alpine' hydrology theory so it's worrying if the model doesn't produce that. If you are getting no spring event its possible your overwinter basal water pressures are too low. This is also possibly why your summer deceleration events are not below the winter mean velocity Overwinter the basal water pressure should be at overburden pretty much everywhere so any water input in the spring will cause a velocity increase. It would be good to include the overwinter steady state ice flux/basal water pressure diagrams, perhaps in supplementary material.

This sentence is discussing the overall magnitude of velocity at the lowest GPS stations in comparison with the other stations, rather than the temporal variability. We have, however, reworded this section to make this clearer, and to point out more clearly the modelled velocity increase in the early summer. We hesitate to call this a 'spring event', as some aspects of this in some years seem heavily controlled by the melt model inputs, which for 2009 especially do not match the observed melt. We also give a detailed discussion on model fit, and possible sources of uncertainty, at the lowest 2 GPS sites on P25 L5-18, with a further discussion on what likely needs to be done to address this on P27 L19-27.

The model predicts low ice velocities throughout most of the summer melt season at the three GPS sites closest to the margin. In general, measured GPS velocities are also relatively low, except for early season high magnitude variability observed at sites S1-S3 (Figure \ref{fig:intRun2009}a-c) in 2009, and at sites S1-S2 in 2011 (Figure \ref{fig:intRun2011}a-b). This observed variability in the GPS velocities precedes melt predicted by RACMO2.3 and is not reproduced by the model. At site S1, modelled velocities show some limited acceleration during the early summer in both 2009 and 2011, but to a lesser extent than in the observed velocities. The fit improves at site S3 for both years, as modelled velocities in 2009 approximate observed velocities (following the early onset of increased summer velocity in the observed data), and in 2011 the model predicts the early summer speedup more effectively.

Figures of winter subglacial effective pressures and the thickness of the distributed sheet (there is no channelization) are available in Koziol and Arnold (2017 – The Cryosphere – Figure 7), as are winter ice velocities (modelled, and winter mean from the Measures dataset). Also, the first frame of the supplementary videos is the winter state.

17-18: ‘In 2009, site S6 shows a gradual. . .’ do you mean the model or the data? Here and elsewhere be careful to specify.

Updated to specify measurements

33: Why qualitatively? A correlation should definitely be quantitative.

Melt and ice velocity response do not have a simple relationship; we don't think this data is suited to simply fitting a linear regression due to the possibility of lagged responses between melt, model response and observation. In this sentence, we are not using correlation in the strict, statistical sense, but rather we are alluding to the fact that observed velocities at the lowest stakes do not ‘fit’ with measured ablation; given this, and as we discuss later, there are many possible causes for the model to not reproduce some of the aspects of the observed velocity. Although we dedicated a few days investigating time series analysis methods, the changing lags, gaps in the data and other factors made led us to feel that a qualitative description of the model results and the fit was the best approach. Ultimately, a useful comparision would be to ensure that the statistical relationship between modelled velocity and modelled runoff is similar to that of measured runoff and measured velocities.

PG 17
7-8: ‘In this section. . .’ awkward sentence.

Rewrote as:

In this section we focus on the sensitivity of the model to the setup, to K_s, and to σ.

11: units! Please check the rest of the manuscript to make sure you include units for all of your numbers.

Updated

18: I don’t understand this. Where does the water go? Also there should definitely be a velocity response (albeit a short one) to a lake drainage event. What is your model timestep by the way?

We have expanded this paragraph to clarify that this discussion refers to a sensitivity experiment in which the input of water from a lake during a hydrofracture event itself is ignored, and effectively removed from the system, in order to better understand the possible impact of such events on season-long velocity patterns. We also amend the sentence to state we are referring to the GPS stations, as none of the GPS stations coincide with a lake that drains. This adds to our finding that the overall behaviour of the model is not sensitive to hydrofracture events. The short-term, localised impact of such events can be seen in the supplementary videos of model results, even though some aspects of the model are not suited for capturing the short term velocity events of lake drainages (and this is not our purpose), since it doesn't incorporate processes such as elastic uplift.

Lake hydrofracture events result in a large volume of water rapidly draining to the base during the *event itself, and a surface-to-bed connection which drains water for the remainder of the melt season. The impact of the initial rapid delivery of water on the model behaviour is tested by running a simulation where the water in a lake when hydrofracture occurs was not input to the base, but removed from the system. The impact on modelled ice velocities at GPS stations (none of which are near lakes which undergo hydrofracture) was found to be negligible. The season-long average velocity across the catchment was also not affected.*

The subglacial hydrology model uses an implicit Euler method with an adaptive timestep.

23: 50% of the initial nodes? What does that mean? Also why these % numbers?

We update this to read 'grid nodes'. This sentence talks about the spatial variability of K_s values. We think talking about the percentage of grid nodes rather than absolute number is preferable.

30: how much was englacial storage increased and reduced?

We amend the sentence as:

A better fit was observed with decreased englacial storage (σ = 10^-4) for 2009 and increased englacial storage (σ = 10^-3) in 2011.

33: day 2015?

Fixed as 205

PG18
1: I'm getting confused what the difference is between the calibration and the validation runs.
On Page 11, we write:

Two simulations are run calibrating the model using data and inputs for 2009 and 2011. Another simulation is then run validating the model with data and inputs for 2012.

To try to clarify this further, we modify the P18 L1 as:

The integrated model is validated against GPS velocity measurements from 2012 (Fig. \ref{fig:intRun2012}), using the parameter values determined in the calibration.

14: accelerating rate of speed-up is poor phrasing

We update it as:

The high melt scenarios show faster flow early in the summer and higher peak velocities (Fig. \ref{fig:intRunFuture})

15-16: modeled velocities decrease during periods of slower flow. The sentence is circular and doesn't make sense.

We have clarified this sentence to make the meaning clearer, and we have re-worded this paragraph to draw out more clearly the spatial and temporal changes between the GPS sites for these three runs.

The high melt scenarios show faster flow early in the summer and higher peak velocities (Fig. \ref{fig:intRunFuture}). After the early summer speedup at sites S1-S3, simulations 2011, 2011x2, and 2011x4 predict broadly similar velocities, although the 2011x2 and 2011x4 runs show slightly lower values overall; this effect can be seen most clearly at site S3. As elevation increases, modelled velocities in the high melt intensity runs decrease more during slow-flow/low melt periods (e.g. days 210-230 at S4). At sites S4-S6, increased melt intensity results in higher variability of ice flow, with higher peak velocities in the first half of the summer season, but with similar low velocities during low melt periods. The relative increase of peak velocities between 2011x2 and 2011x4 is greater than between 2011 and 2011x2. At these sites, the model predicts broadly similar velocities in all three simulations for the latter half of summer, from days 210 to 238, but at site S4, model velocities are lowest for the 2011x4 scenario, whereas at site S6, modelled velocities increase slightly with greater melt input. Site S5 shows mixed behaviour, with model velocities from simulation 2011x4 higher than the other simulations between days 210 and 222, but lower between days 223 and 236. Between days 210 and 238 at sites S4-S6, model velocities are low and only slightly elevated above their winter values. At site S7, the velocities in the increased melt intensity simulations are faster than 2011 velocities, and with some periods where the 2011x4 scenario generates the slowest velocities (e.g. days 198 and 210), when short-term melt rates drop after a period of higher melt and velocity. Starting at day 238, a late season velocity spike is observed, most strongly at sites S4 and S5, though apparent at other sites. The melt input during this period decreases with elevation, but the impact of this event increases strongly with elevation to sites 4-5, but then decreases at sites S6 and S7.

PG21
2: Why does figure 12 compare 2009 with 2011 x 4? Why not 2011 and 2011x4?

We selected 2009 as the slowest year to show the maximum impact of increasing melt.

From this figure it seems like melt increase has a significant impact on the velocity of most of your domain, just not at the very margin. This seems to be understated in your arguments, which are more focused on confirming a model that suggests more water = velocity decrease.

We have reworded this paragraph to show the spatial variability in response more clearly.

Melt season averaged modelled velocities at the GPS sites are shown in Figure \ref{fig:seasonalAvGPS}. Average velocities are highest at GPS site S4, and decrease towards the ice margin, and at high elevations. Average velocities increase with melt season intensity at all GPS sites, with a pattern skewed away from the sites closest to the ice margin which show the least sensitivity. As melt season intensity increases, velocities in the upper ablation zone and at the equilibrium line (located at 1500 \unit{m} elevation \citep{VandeWal2015}, slightly above S6) are predicted to increase the most, scaling with melt (comparing 2011, 2011x2, and 2011x4); site S7, with the lowest melt, shows more limited sensitivity. The pattern observed at the GPS stations is generally reflective of that across the study domain (Figure \ref{fig:seasonalAvSpatial}); areas between around 800m and 1400m show the largest increase, but with areas of slower flow predicted to accelerate more than areas of faster flow. Average velocities between 2009 and 2011x4 increase by up to 70\%.

15: the fact that you have channels forming at higher elevations but still get speedup tells you a lot about the system that you haven't discussed. This feeds into one of my major comments about

the presence of channels not necessarily facilitating efficiency. It depends how much water those channels remove from the distributed system and therefore the change in effective pressure.

We accept this point, here and elsewhere, and we have reworded some aspects of our discussion and conclusion to reflect this argument.

PG25
10: a high aspect ratio of what?

We've removed the first part of the sentence.

16: cite Schoof et al (2014), The Cryosphere.

Updated

PG26

3: 'affected'

Updated

24: what is this constant sheet height scale? How does this link to the previous sentence?

This was an error; this is actually the bed roughness height scale. It links to the previous sentence as it refers to properties of the distributed sheet.

27-32: these ideas have been around for a while so you need to reference this paragraph (e.g. Das et al, 2008, Doyle et al, 2013, Dow et al, 2015, Banwell et al, 2016). Also GPS data show that lake drainage have a large impact on ice velocities, just in the short term. What this means is that your model outputs are not valid for this particular lake hydrofracture example and therefore you have to be careful using them to make strong arguments.

As we have discussed above, we also re-word this paragraph to make it clear that we mean hydrofracture events in themselves have little impact on season-long, catchment-wide velocity (even though they do impact short-term, local velocity, which the model does show). Our discussion here is focuses on the long-term and large-scale development of the subglacial hydrology system where lake hydrofracture events in themselves do not act as a primary control. We add some citations here to reflect this, including an additional paper (Hoffman et al. 2018) which builds on the argument that the real importance of lake hydrofracture events is in establishing surface-to-bed connections.

The initial rapid delivery of a large volume of water to the bed during individual lake hydrofracture events is not observed to have a lasting or widespread effect on modelled velocities (in line with observations by \citet{Hoffman2011}). This suggests that lake hydrofracture events in themselves are not a key process in the long term or large scale development of the subglacial hydrological system, as at lower elevations, the numerous conduits and high water input drive channelization, while at higher elevations, a combination of insufficient input and conditions unfavourable for channelization exist. Rather, the primary impact of lake hydrofracture is in opening surface-to-bed connections. The spatial density of such events has been shown to affect the rate of development of channelized drainage \citep{Banwell2016}, and to act as a key mechanism for the creation of moulins away from crevasse *fields or current lake basins \citep{Hoffmann2018}, which then drain a significant proportion of the overall surface melt as we find in this study, and previous work \citep{Koziol2017}.*

PG 27
13: low aspect ratio and low sliding ratio. Ratios of what?

Aspect ratio and sliding ratio are commonly used terms in model derivations. They refer to the vertical scale of ice over the horizontal lengthscale, and the basal velocity over surface velocity respectively.

We also note low aspect ratio is a typo, and should read high aspect ratio.

PG 28
18 (+PG30 6-7): This depends on what you class as the margin. This seems to only apply to within ~40km of the terminus.

We have modified this phrase to say '*closer to the ice margin*'.

PG29
1-8: You're model doesn't support the assertion that channels further inland will cause slowdown. Even though you have more channels, there is still velocity increase at your upper site.

Further to our responses listed above (to the general comments, and P21 L15), we discuss this aspect of our model in more detail here.

11-12: why would winter velocity decrease? This doesn't make sense if velocities are faster in the higher melt scenarios implying widespread distributed drainage. And what do you mean by offset?

The idea of a winter velocity decrease comes from observational studies which suggest summer melt affects winter velocity, with high melt leading to slower flow in winter due to the ongoing impact of basal hydrology (e.g. Tedstone et al. 2015, van der Wal et al. 2015). We also refer the reviewer to the recent review Nienow (2017)), which discusses this phenomena at higher elevations as well. We are arguing that a summer increase due to higher melt could offset the impact of a winter decrease on the annual average velocity.

Table 1:
-Ks is called sheet hydraulic conductivity in the text

We went through the text to standardize this, Ks should be the sheet flux coefficient

-is K the hydraulic conductivity for the channel or the sheet? And do you mean m sˆ-1? 2m sˆ-1 is really fast!

K is now deleted.

- a critical layer depth of 1 m seems high given the basal bumps are 0.1 m high. - what is the difference between Am and Sm?

Critical depth layer is deleted; however, the bed roughness height scale should have read 0.5m. Sm is updated to Am.

Table 2:
- I don’t think defining the number of seconds in a year is necessary.

We keep it for completeness

Fig 1: caption needs a date for the satellite image

Updated

Fig 3: I don’t really understand what this schematic is showing. It’s not immediately obvious.

Following from the other reviewer's comments, we shaded the crevassed area in the figure to highlight it more clearly, and we have re-worded the caption to make it clearer that all melt which occurs within an internal catchment within a crevasse field is assumed to drain into the moulin at the edge of the catchment.

Fig 7/8: An indication of the elevation for each site would be useful here

The focus here is on the model fits, but we have updated Fig 10 to allow a better understanding of average seasonal velocities at different elevations

Fig 14: It’s really hard to tell the difference between the sheet and channel curves

Updated the figure to use dashed line instead of dash-dot line

Modelling seasonal meltwater forcing of the velocity of land-terminating margins of the Greenland Ice Sheet

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Abstract. Surface runoff at the margin of the Greenland Ice Sheet drains to the ice-sheet bed leading to enhanced summer ice flow. Ice velocities show a pattern of early summer acceleration followed by mid-summer deceleration, due to evolution of the subglacial hydrology system in response to meltwater forcing. Modelling the integrated hydrological - ice dynamics system to reproduce measured velocities at the ice margin remains a key challenge for validating the present understanding of the system, and constraining the impact of increasing surface runoff rates on dynamic ice mass loss from the ~~GrIS~~Greenland Ice Sheet. Here we show that a multi-component model incorporating supraglacial, subglacial, and ice dynamic components applied to a land-terminating catchment in western Greenland produces modeled velocities which are in ~~good~~ reasonable agreement with those observed in GPS records for three melt seasons of varying melt intensities. This provides numerical support for the hypothesis that the subglacial system develops analogously to alpine glaciers, and supports recent model formulations capturing the transition between distributed and channelized states. The model shows ~~development of efficient conduit~~ the growth of efficient conduit-based drainage up-glacier from the ice sheet margin, which develops more extensively, and further inland, as melt intensity increases. This suggests current trends of decadal timescale slow-down of ice velocities in the ablation zone ~~will~~ may continue in the near future~~, although the strong summer velocity scaling in our results could begin to offset potential future fall and winter velocity decreases for very high melt rates which are predicted for the end of the 21st century~~. The model results also show a strong scaling between average summer velocities and melt season intensity, particularly in the upper ablation area. Assuming winter velocities are not impacted by channelization, our model suggests an upper bound of a 25% increase in annual surface velocities as surface melt increases to 4x present levels.

1 Introduction

~~Seasonal acceleration at the GrIS margin is driven by surface~~ Surface meltwater draining into the subglacial system ~~.~~ drives seasonal acceleration of ice velocities at land-terminating sectors of the Greenland Ice Sheet margin. It may also be an important factor for seasonal accerlation of marine-terminating sectors (Howat et al., 2010; Sole et al., 2011; Moon et al., 2014). Increased water pressures reduce basal drag by decreasing ice-bed coupling, leading to faster ice flow. Early in the summer, surface runoff drains into an inefficient hydrological system, elevating water pressures and accelerating ice flow (Bartholomew et al., 2011; Fitzpatrick et al., 2013; Sundal et al., 2011). As the melt season progresses, a channelized system that efficiently drains water develops. This reduces water pressures and leads to a late summer deceleration (Bartholomew et al., 2010; Chandler et al., 2013; Cowton et al., 2013; Schoof, 2010). Understanding the impact of increased surface melting (Hanna et al., 2013; van den Broeke et al., 2009) on the spatial and temporal evolution of basal hydrology is important for constraining the GrIS's future evolution. If increased summer melt intensity drives faster mean annual velocities, than a positive feedback between surface melt and ice flow would contribute to mass loss from the GrIS in a warming climate (Zwally et al., 2002). Faster ice flow would draw ice down to lower elevations, where the melting is greater, which in turn drives faster ice flow.

Observations do not show a simple relationship between surface runoff and ice velocities however. Decadal-timescale observations in Southwest Greenland of land terminating sectors show mean annual velocities decreasing in the ablation zone (Stevens et al., 2016; Tedstone et al., 2015; van de Wal et al., 2015). However reported correlation between summer melt intensity and mean annual ice velocities from these studies are either slightly negative, or nonexistent. In the accumulation zone, decadal-timescale measurements are sparse and the data inconclusive about velocity trends (Doyle et al., 2014; van de Wal et al., 2015). Measurements on a daily timescale in the ablation zone show that increased melt intensity can lead to faster ice flow early in the summer. However, the impact of increased ice motion early in the summer on the average annual velocity can be offset by an earlier onset of channelization and corresponding deceleration as the melt season progresses (Sundal et al., 2011; van de Wal et al., 2015). Increases in channelization extent may also lead to slower mean winter flow, due to more extensive drainage of the subglacial system leading to lower water pressures during winter (Sole et al., 2013). As melt season intensity continues to increase, it remains unclear how ice velocities ~~may be altered due to changing patterns of input , and input~~ will be forced by water input at higher elevations where ice thickness is greater, and whether patterns of water input at higher elevations will change (Leeson et al., 2015; Poinar et al., 2015; Cooley and Christoffersen, 2017).

Numerical models can provide insight into the hydrological processes driving faster summer flow. Recent subglacial hydrology models have progressed to simultaneously incorporating both distributed and efficient systems, explicitly treating the interaction between the two (Hoffman and Price, 2014; de Fleurian et al., 2016; Hewitt, 2013; Pimentel and Flowers, 2010; Schoof, 2010; Werder et al., 2013). Current models can reproduce the observed upglacier development of the efficient system through the melt season. When coupled to an ice sheet model, the results broadly reproduce the observed velocity patterns of the GrIS margin (Hewitt, 2013; Pimentel and Flowers, 2010). However, recent hydrological models coupled to an ice flow models have not been applied to real domains of the GrIS to model large-scale behaviour of the ice-margin during the summer melt season . Rather, applications to real domains of the GrIS for the summer melt season have either omitted ice flow (Banwell et al., 2016; de Fleurian et al., 2016), used a simplified hydrological model coupled to ice flow (Bougamont et al., 2014; Colgan et al., 2012), or focused on a small domain (Hoffman et al., 2016). Coupling recent hydrological models with ice sheet models allows for ~~an~~ important feedback between the distributed system and ice velocities (Bartholomaus et al., 2011; Hoffman and Price, 2014), and allows explicit comparison between GPS velocities and model output. Comparisons to surface ice velocity measurements are an important means for validating subglacial hydrological models, and provide a method for constraining poorly understood aspects of subglacial hydrology (see review by Flowers, 2015). Present challenges in applying coupled ice dynamics/hydrology models to the GrIS margin for modelling seasonal evolution include: the values of parameters; the form of the sliding law which relates water pressures to basal drag; and whether the models presently include the necessary elements.

Additionally, modelling surface hydrological input to ~~the drive the~~ drive the subglacial hydrology model is in itself a challenge. A variety of ~~different~~ methods have been employed, incorporating different drainage elements (e.g. Banwell et al., 2016; Bougamont et al., 2014; de Fleurian et al., 2016). However, no model ~~to date has included the full spectrum of supraglacial drainage pathways~~including drainage via all of crevasses, moulins, and lake hydrofracture has been used to force a subglacial hydrology model to date.

This paper aims to model summer ice flow in the land-terminating Russell Glacier area of western Greenland for three contrasting melt seasons using a multicomponent model approach similar to the previous work of Arnold et al. (1998) and Flowers and Clarke (2002) on alpine glaciers. The model is then used to test the ice sheet response to higher melt input. A coupled hydrology-ice flow model is produced by integrating a subglacial hydrology model (Hewitt, 2013) with the ice flow model of Koziol and Arnold (2017). This coupled model is driven by surface input from the surface hydrology-lake filling model ("SRLF" model) from Koziol et al. (2017), and initiated using the inversions from Koziol and Arnold (2017). The Russell Glacier area is selected as a study site to take advantage of the numerous observations available. These observations include radar flight lines constraining bed topography (Morlighem et al., 2015), meteorological data constraining climatic input (Noël et al., 2015), and GPS data (Tedstone and Neinow, 2017) which provide a calibration and validation data set for model output.

2 Methods

The methods section begins with a description of the Russell Glacier study area and the data sets used. The study site is presented first so that the domain can be referred to when describing the boundary conditions applied in the models. Each individual model is then briefly described, before detailing how the models are linked. The coupled ice flow/subglacial hydrology model is referred to as the 'integrated model' for simplicity. Finally, the modelling workflow is described.

2.1 Study Area and Datasets

The Russell Glacier area is a land-terminating sector of the GrIS in Southwest Greenland. The study area boundaries for the SRLF model and the integrated model are shown in Fig. 1. The domain of the SRLF runs is selected to be larger than the integrated model domain to minimize the impact of boundary conditions. A 6 km buffer is used at the northern and southern boundaries of the SRLF domain, based on the reported internally drained catchments by Yang and Smith (2016). The SRLF domain extends 8.5 km to east of the integrated model study site to capture as much higher elevation melting as possible. The domain of the SRLF model is discretized at a 90 m resolution, while the domain of the integrated model is discretized at a 1000 m resolution.

Two different topography datasets are used. The SRLF model is run ~~with the 90 resolution~~ using surface topography from the GIMP dataset (Howat et al., 2015). The high resolution surface topography is necessary for accurate water routing and so that lake basin topography is accurately preserved. The integrated model is run with surface and bed topography from BedMachine2 (Morlighem et al., 2014, 2015) to take advantage of the mass-conservation methods used to determine basal

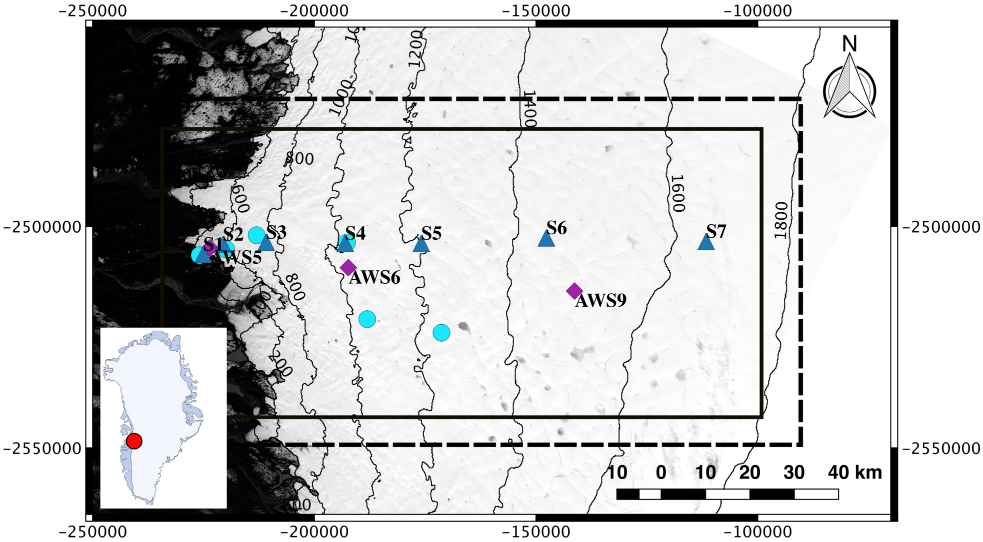

Figure 1. Landsat 8 satellite image acquired on 19 August 2013, band 2, showing the Russell Glacier area. Black solid rectangle outlines the study domain for the integrated model, while the black dashed rectangle outlines the SRLF study domain. The blue triangles show the locations of GPS stations (Tedstone and Neinow, 2017). Purple diamonds show the locations of automatic weather stations (van de Wal et al., 2015). Cyan circles show the ~~loactions~~ locations of moulins used as tracer injections sites in Chandler et al. (2013). Inset shows the location in reference to Greenland.

topography. BedMachine2 provides both topographic datasets at 150 m, although the true resolution is reported as 400 m. This data is reinterpolated to 1000 m resolution.

Surface runoff and snow depth data for the SRLF model are provided by RACMO2.3 (Noël et al., 2015). Both runoff and snow depth are bilinearly interpolated from 11 km~~to 90~~. Three seasons with contrasting melt volumes are modelled: 2009, 2011, and 2012 (Fig .2). Total melt over the SRLF study domain was $1.2 \cdot 10^{10}$ m^3 in 2009, $1.7 \cdot 10^{10}$ m^3 in 2011, and $2.1 \cdot 10^{10}$ m^3 in 2012. ~~These three years serve as analogues for summers with with~~ Following Koziol et al. (2017) , we use these three years as representative of summers with average, elevated, and extreme melt intensity respectively~~(following Koziol et al. (2017))~~.

Mean winter velocities are used for inversions of winter basal boundary conditions (see Section 2.6) and to determine crevasse locations as an input to the SRLF model. Mean winter velocities for 2008-2009 are provided at 500 m resolution by the MEaSUREs Greenland Ice Sheet Velocity Map dataset (Joughin et al., 2010a, b). For the inversion procedure, the winter velocities, along with their associated errors, are reinterpolated to 1000 m. Velocities at 500 m resolution are used to determine surface stresses, assuming an ice temperature of -5 C. Crevassed areas are then calculated using a von Mises stress criterion following Clason et al. (2015). A crevassing threshold is selected by comparing the von Mises stress to observed patterns of crevassing in a Landsat 8 image~~.~~ , acquired on 19 August 2013. A threshold value of 145 kPa ~~is selected as optimal~~gave the best visual match.

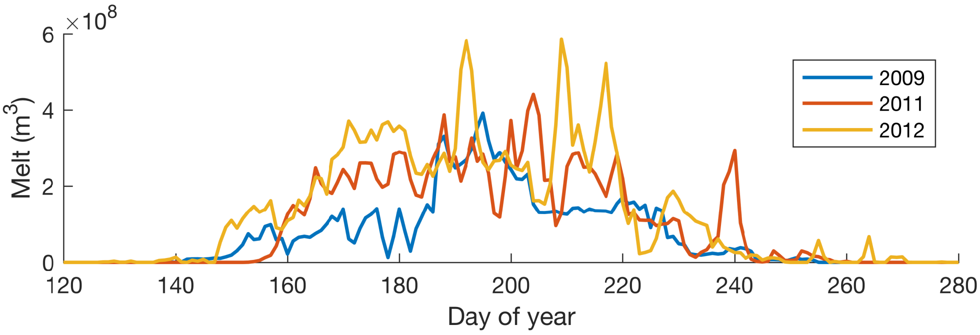

Figure 2. Daily surface runoff over the SRLF Russell Glacier study area for three contrasting summer melt seasons.

Moulin locations are specified as input data in the SRLF model. Moulin locations in the Russell Glacier area reported by Yang et al. (2015) are used. These were derived automatically from a Landsat 8 image acquired on 19 August 2013, using an algorithm which determines where streams are observed to abruptly disappear (Yang et al., 2015). As in Koziol et al. (2017), moulin locations which do not coincide with a stream location calculated by the surface routing algorithm are slightly adjusted, such that they are located on a stream. A small number of moulins from the dataset are deleted, as they were not near a calculated stream, and hence would drain negligible water.

A key validation dataset in the Russell Glacier area is GPS surface velocity measurements for 2009-2012 (Tedstone and Neinow, 2017). A time series of hourly and daily averaged surface speeds are provided in the dataset. Here, the daily averaged speeds are used for comparison with model results. The locations of GPS stations are shown in ~~in~~ Fig. 1.

2.2 Supraglacial Hydrology (SRLF)

We use the supraglacial hydrology model (SRLF) from Koziol et al. (2017), run at 90 m resolution. A no-inflow boundary condition is imposed on all boundaries. Water is routed using a DEM of the surface of the ice sheet and a single flow direction algorithm (Arnold et al., 1998; Tarboron, 1997). Water can enter the subglacial system via drainage into pre-existing moulins or crevasses, and is also allowed to drain off the edge of the domain, or over the western ice margin. Water also collects in depressions in the surface DEM forming lakes. Lakes which are predicted to hydrofracture ~~(Das et al., 2008; Stevens et al., 2015)~~ (Das et al., 2008; Stevens et al., 2015), using a fracture area criterion, drain to the ice-bed interface and create a ~~surface to bed~~ surface-to-bed connection (treated as a moulin) for the remainder of the melt season. Lakes can also drain over the surface of the ice sheet via "overspill" drainage and "channelized" drainage. Overspill drainage refers to when water exceeding the capacity of the lake is routed downstream, with no incision of a channel at the lake edge. Channelized drainage refers to when water is routed downstream, but incises a channel at the lake edge, which allows slow lake drainage. Channel incision is modelled following Raymond and Nolan (2000). Overspill and channelized drainage can occur simultaneously if water enters a lake faster than can be evacuated by an existing channel alone.

2.3 Subglacial Hydrology

We use the subglacial hydrology model presented in Hewitt (2013) and Banwell et al. (2016). Distributed flow occurs through a continuum 'sheet', composed of a cavity sheet component and an elastic sheet component. The latter is included so that during lake hydrofracture events 'hydraulic jacking' is simulated. Channels can form along the edges and diagonals of the rectangular finite difference mesh. Dissipative heating over an incipient ~~channel-width length-scale~~ channel width lengthscale provides the initial perturbation for channel initialization. Water input occurs at moulins located at cell nodes, which along with an englacial aquifer, allow for water storage. The model is run at 1000 m resolution. At the ice-margin edge an atmospheric pressure boundary condition is imposed, while the remaining boundaries have a no-flux condition. A concise model description is given here following Hewitt (2013) and Banwell et al. (2016) to provide context for the parameters used. However, for a detailed description the reader is referred to Hewitt (2013) and Banwell et al. (2016).

Discharge in the continuum sheet is modelled as:

$$\mathbf{q} = -\frac{Kh^3}{\rho_w g}\frac{K_s h^3}{\rho_w g}\nabla\phi \tag{1}$$

where $h(x,y)$ is the thickness of the continuum sheet, K_s is the sheet ~~hydraulic conductivity~~flux coefficient, g is the acceleration due to gravity, ρ_w is the density of water, and ϕ is the hydraulic potential. The hydraulic potential is defined as $\phi(x,y) = \rho_w g b(x,y) + p_w(x,y)$, where p_w is water pressure and $b(x,y)$ is the bed elevation.

The distributed sheet thickness (h) is the sum of the thickness of the cavity sheet ($\cancel{h_c}h_{cav}$) and the elastic sheet (h_{el}). The cavity sheet evolves according to:

$$\frac{\partial h_{cav}}{\partial t} = \frac{\rho_w}{\rho_i}m + U_b\frac{h_r - h_{cav}}{l_r} - \frac{2A_b}{n^n}h_{cav}|N|^{n-1}N \tag{2}$$

where ρ_i is the density of ice, m is the basal melting rate, U_b is the basal sliding speed, h_r is the bed roughness height scale, l_r is the bed roughness length scale, A_b is the ice creep parameter, n is the exponent from Glen's flow law, and $N(x,y)$ is the effective pressure. The effective pressure is defined as $N = \rho_i g H - p_w$, where H is the ice thickness~~, p_w is water pressure~~.

Basal melt rate is given by:

$$m = \frac{G + \tau_\mathbf{b}\cdot\mathbf{u_b}}{\rho_w L} \tag{3}$$

where $\tau_\mathbf{b} = (\tau_{bx}(x,y), \tau_{by}(x,y))$ is the basal drag, $\mathbf{u_b} = (u_b, v_b) = (u(x,y,b), v(x,y,b))$ is the basal velocity, G is the net conductive flux, defined as the geothermal heat flux minus conductive loss into the ice, and L is latent heat.

The elastic sheet thickness is given by:

$$h_{el} = C_{el}\left[-N_- + \frac{1}{2}N_0 \cancel{max}\max(0, 1 - \frac{N_+}{N_0})^2\right] \tag{4}$$

where ~~$N_- = min(N,0)$, $N_+ = max(N,0)$~~$N_- = \min(N,0)$, $N_+ = \max(N,0)$, C_{el} is an elastic compliance, and N_0 is a regularization parameter. When effective pressure is positive, this layer is designed to be zero. As effective pressure approaches zero or is negative, the thickness is determined by the product of the elastic compliance and effective pressure (Banwell et al., 2016).

Discharge in channels is modelled as:

$$Q = -K_c S^{5/4} |\frac{\partial \phi}{\partial r}|^{-\frac{1}{2}} \frac{\partial \phi}{\partial r} \tag{5}$$

where K_c is a turbulent flow coefficient, S is channel cross-section, and r is along channel distance.

The channel cross section evolves according to:

$$\frac{\partial S}{\partial t} = \frac{\rho_w}{\rho_i} M - \frac{2A_b}{n^n} S|N|^{n-1} N \tag{6}$$

where M is the melting rate along the channel wall.

The melting rate along the channel walls is given by:

$$M = \frac{|Q \frac{\partial \phi}{\partial r}| + \lambda_c |q \cdot \nabla \phi|}{\rho_w L} \tag{7}$$

where λ_c is an incipient channel width lengthscale (melting of basal ice over this scale contributes to channel initialization).

The equation for mass conservation is:

$$\frac{\partial h}{\partial t} + \nabla \cdot \mathbf{q} + \left[\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial r} \right] \delta(\mathbf{x}_c) + \frac{\partial \Sigma}{\partial t} = m + M\delta(\mathbf{x}_c) + R\delta(\mathbf{x}_m) \tag{8}$$

where Σ is englacial storage and R is the supraglacial input ~~to moulins,~~ rate to moulins. The delta functions apply along channels ($\delta(\mathbf{x}_c)$) and the positions of moulins ($\delta(\mathbf{x}_m)$).

Englacial storage is represented as

$$\Sigma = \sigma \frac{p_w}{\rho_w g} + A_m \frac{p_w}{\rho_w g} \delta(\mathbf{x}_m) \tag{9}$$

where σ is englacial void fraction and A_m is moulin cross sectional area.

Model parameters held constant are shown in Table 1. Two parameters ~~are assigned a spatially heterogeneous distribution in the calibration. The englacial storage parameter is assigned a background value of 10^{-3}, with 50% of the cells then randomly set to 10^{-4}. The effective sheet conductivity field is constructed using a background value of 10^{-2}, with 15% of the cell nodes randomly assigned a value of 10^{-7}. Since sheet conductivity is defined on the grid, neighboring nodes are averaged in the x and y directions to determine values on edges. At a sheet depth of 0.1 , a sheet hydraulic conductivity of 10^{-2} results in an effective hydraulic conductivity kh^2~~ of ~~10^{-4} (Hewitt, 2013) . This is at the upper end of values for till, which are inferred to be 10^{-4} to 10^{-9} (Fountain and Walder, 1998). The secondary value of 10^{-7} for sheet conductivity assigned at nodes was selected to give an effective hydraulic conductivity at the opposite end of the spectrum~~the subglacial hydrology model, K_s and σ are the focus of calibration experiments. They were identified in (Hewitt, 2013) and (Banwell et al., 2016) as key parameters determining the morphology of the subglacial hydrology system.

Symbol	Constant	Value	Units
ρ_w	water density	1000	$\mathrm{kgm^{-3}}$
ρ_i	ice density	917	$\mathrm{kgm^{-3}}$
g	gravitational constant	9.8	$\mathrm{ms^{-2}}$
n	exponent in glen's flow law	3	
A_b	creep parameter	$7 \cdot 10^{-24}$	$\mathrm{Pa^n s^{-1}}$
L	latent heat	$3.35 \cdot 10^5$	$\mathrm{Jkg^{-1}}$
S_m	moulin area	10	$\mathrm{m^2}$
σ	englacial void fraction	see text	
K_s	sheet flux coefficient	see text	$\mathrm{Pa^{-1}s^{-1}}$
K_c	turbulent flow coefficient	0.1	$\mathrm{ms^{-1}Pa^{-0.5}}$
λ_c	incipient channel width	10	m
~~K hydraulic conductivity 2~~ h_r	bed roughness height scale	~~0.1~~ 0.5	m
l_r	bed roughness length scale	10	m
h_c	critical layer depth	1	m
C_{el}	elastic compliance	$1.02 \cdot 10^{-5}$	$\mathrm{mPa^{-1}}$
A_m	moulin cross sectional area	10	$\mathrm{m^2}$
N_0	regularization pressure	10^3	Pa

Table 1. Constants used in the subglacial hydrology model during integrated runs in the Russell Glacier area.

2.4 Ice Flow/Inversion

The ice flow model implements the hybrid formulation of the ice sheet stress balance (Arthern et al., 2015; Goldberg, 2011), which can be considered a combination of shallow ice approximation and shallow shelf approximation. The model implicitly accounts for depth varying ice flow, and surface velocities can be explicitly calculated when comparing model output to GPS measurements. This model is similar to the one used in (Hewitt, 2013), except the conservation of momentum equations are a function of depth integrated velocities rather than basal velocities. Parameters for the model are listed in Table 2. A Dirichlet boundary condition is imposed on all lateral domain margins except the ice-margin, where the standard boundary condition based on the continuity of stress is used. A no penetration boundary condition is applied at the edge of the nunatak (Fig. 1). Three sliding laws are implemented:

$$\tau_\mathbf{b} = \beta^2 \mathbf{u_b} \tag{10}$$

$$\tau_\mathbf{b} = \mu_a N_{\cancel{+}sl}{}^p U_b{}^q \frac{\mathbf{u_b}}{U_b} \tag{11}$$

Symbol	Constant	Value	Units
A	Ice-flow parameter	$7 \cdot 10^{-25}$	$\mathrm{Pa^n s^{-1}}$
A_b	Ice-flow parameter for basal ice	$7 \cdot 10^{-24}$	$\mathrm{Pa^n s^{-1}}$
ρ_i	Ice density	917	$\mathrm{kgm^{-3}}$
g	Gravitational constant	9.81	$\mathrm{ms^{-2}}$
n	Exponent in Glen's flow law	3	
p	Exponent ~~generalized Weertman~~ in Budd sliding law	3^{-1}	
q	Exponent ~~generalized Weertman~~ in Budd sliding law	3^{-1}	
λ_b	bed roughness scale	1	m
t_y	Seconds per year	31536000	$\mathrm{syr^{-1}}$
ϵ	viscosity regularization parameter	$1 \cdot 10^{-14}$	$\mathrm{ms^{-1}}$

Table 2. Constants used in the ice sheet/inversion model applied to the Russell Glacier Area.

$$\tau_{\mathbf{b}} = \mu_b N_{\cancel{+}sl} \left(\cancel{\frac{U_b}{U_b + \lambda_b A_b N_+^n}} \frac{U_b}{U_b + \lambda_b A_b N_{sl}^n} \right)^{\frac{1}{n}} \frac{\mathbf{u_b}}{U_b} \tag{12}$$

where $\beta(x,y)$ is a basal drag coefficient, $\mu_a(x,y)$ is a drag coefficient, p and q are positive exponents, $\mu_b(x,y)$ is a limiting roughness slope, λ_b is a bed roughness length (Hewitt, 2013). Following Hewitt (2013), negative effective pressures are eliminated by setting $\cancel{N_+ = max(N,0)}$ $N_{sl} = \max(N,0)$, and regularized with a small ~~regularization constant~~ constant (10^2 Pa).

The linear sliding law (Eq. 10) is used for the initial inversion of winter mean velocities, while the ~~Weertman~~ Budd (Eq. 11) (Budd et al., 1979; Hewitt, 2013) and Schoof (Eq. 12) (Gagliardini et al., 2007; Schoof, 2005) sliding laws are used subsequently. The linear sliding law uses a single parameter to represent all the processes at the ice-bed interface, while the non-linear sliding laws attempt to explicitly incorporate the impact of effective pressure and have a more complex dependence on velocity.

The inversion code used in this paper is described in (Koziol and Arnold, 2017). It is based on automatic differentiation methods (Goldberg and Heimbach, 2013; Heimbach and Bugnion, 2009; Martin and Monnier, 2014), and uses the open source Matlab package AdiGator (Weinstein and Rao, 2011-2016). The gradient of the cost function in this method is equivalent to one calculated using Lagrangian multiplier methods (MacAyeal, 1993; Morlighem et al., 2013) to generate the adjoint model (Heimbach and Bugnion, 2009). The cost function ~~minimizes~~ (Eq. 13) has two terms. The first is the weighted square of the ~~difference of squares of~~ differences of measured and predicted velocities~~(Eq. 13). A~~. The second is a Tikanov regularization term ~~is~~ added for stability.

$$J = \gamma_1 \int\limits_{\Gamma_s} w \cdot (U_{obs} - U_s\left(\alpha\right))^2 d\Gamma_s + \gamma_2 \int\limits_{\Gamma_b} (\nabla\alpha \cdot \nabla\alpha) d\Gamma_b \tag{13}$$

where γ_1 and ~~γ_1~~ γ_2 are scaling factors, Γ_s is the surface domain, Γ_b is the basal domain, $w(x,y)$ is a weighting function, $U_{obs}(x,y)$ are observed surface ice speeds, ~~U_s~~ $U_s(\alpha,x,y)$ are modelled surface speeds, and $\alpha(x,y)$ is the control parameter. The control parameter depends on the sliding law, and represents β in the linear sliding law, μ_a in the ~~generalized Weertman~~ Budd sliding law, and μ_b in the Schoof sliding law. The inverse of reported errors of surface velocities are used ~~to calculate weights.~~ as weights. Modelled surface velocities depend on the control parameter via the sliding law. The inversion procedure minimizes the cost function with respect to the control parameter.

2.5 Model Integration

~~Englacial drainage is not considered in the SRLF model~~ The SRLF model is used to determine supraglacial input rates to the subglacial system. For model integration, we assume that water drainage through ~~the englacial system~~ surface-to-bed connections is strictly vertical, ~~and that there is no horizontal transport in the englacial system~~with no horizontal component. The SRLF model routes water into three different ~~surface drainage~~ surface-to-bed pathways: moulins, lake hydrofracture, and crevasses. Moulins and ~~surface to bed~~ surface-to-bed connections from lake hydrofracture are treated identically. All water entering these cells drains ~~directly to the bed~~into the subglacial hydrology system at that location. However, drainage through crevasse field requires additional consideration. When water enters a ~~cell determined as crevassed~~ crevassed cell in the SRLF model, ~~the water is removed from the model, and~~ no further routing occurs. Since it is unlikely that every crevassed grid cell drains water locally to the ice-bed interface, postprocessing of SRLF output is necessary.

Water drainage through crevasse fields is poorly understood, and the scheme implemented here (Figure 3) is motivated by simplicity. We assume all water in crevasse fields drain to bed, neglecting any refreezing. We also assume that contiguous areas of crevassed cells are hydrologically connected~~, perhaps by an internal water table~~. A crevassed cell in the SRLF model can accumulate water from two sources: 1) local ablation predicted by RACMO2.3; 2) a cell which is on the margin of a crevassed area may have water flowing into it from adjacent non-crevassed cells. Modelling predicts approximately 70% of the water drained by crevasses is intercepted water flow over the ice sheet surface (source 2). This water is concentrated at the points where supraglacial streams intersect the crevasse fields. The model assumes that moulins exist at these points, as high water input would be favourable to nucleating and sustaining moulins. Moulins are only placed in cells with sufficient drainage, determined by a volume threshold. A value of $5 \cdot 10^5$ m^3 is selected, corresponding to approximately the median volume drained by moulins outside of lake basins. A lower threshold results in a rapidly increasing number of moulins draining smaller amounts of water. A ~~veronoi~~ Voronoi partitioning is then used around the inferred moulins to create internal catchments within the crevasse field. All water in a catchment is assumed to drain in ~~it's~~ to its corresponding moulin. As stated, the SRLF model does not route water within crevasse fields; there is no travel time associated with melt in the internal catchments of crevasses and the moulin.

The supraglacial model is run independently, to determine a time series and location of water inputs to the base. These are then used as input to the coupled subglacial hydrology/ice flow model. A potential feedback omitted by this approach is the influence of surface velocity on lake hydrofracture. However, the current design and computational requirements of the SRLF model make it impossible to run in a fully coupled manner with the integrated model.

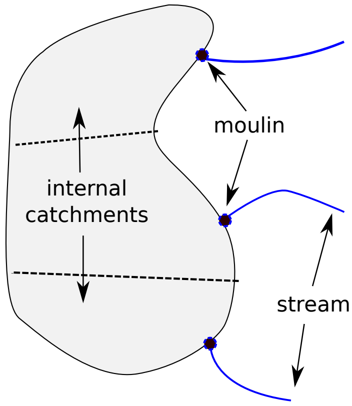

Figure 3. Schematic drawing showing the conceptual model of the crevasse drainage implemented. Shaded area indicates a crevasse field. Moulins are assumed to occur where high-flux supraglacial streams intersect the crevasse field. The crevasse field is ~~than~~ then partitioned using Voronoi partitioning into internal catchments. All ~~water in~~ melt which occurs within an internal ~~catchments drains~~ catchment is assumed to drain into the ~~ice-bed interface~~ subglacial system at ~~its~~ the corresponding moulin.

The integration of the subglacial hydrology and ice flow models mirrors that of Hewitt (2013); the subglacial hydrology uses an implicit timestep using the current ice velocity distribution. After the state of the subglacial hydrology model in the next timestep is calculated, the ice model is called to update ice velocities. At each timestep, the basal melting rate is updated. The geometry of the domain is kept constant for the whole run.

2.6 Workflow

Figure 4 shows the workflow for initializing and running the integrated model. The initial step is to perform an inversion using the linear sliding law over the study area (see Koziol and Arnold (2017) for details of inversions, which are done over the same study area but with a resolution of 500 m). All linear inversions are run using mean winter velocities from 2009, the most recent year for which data were available. This inversion provides an initial distribution of basal drag and basal velocities to calculate the basal melt rate (Eq. 3). The subglacial hydrology model is then run for 240 days holding basal velocities fixed~~;~~ ~~this corresponds~~ , corresponding to a run over a winter season (Sept 1 - April 30). By the end of the run, effective pressures reach an approximate steady state (Koziol and Arnold, 2017). The effective pressures at the end of the subglacial hydrology simulation are then incorporated into an inversion with a non-linear sliding law to determine the background values of the coefficients, μ_a and μ_b. These sliding law coefficients, the basal water pressures, and the surface runoff input from the SRLF model form the inputs to the integrated model. The integrated model is then run for the summer melt season using the end of winter effective pressures as an initial condition. As stated in Koziol and Arnold (2017), a key assumption of this procedure is that the mean winter velocities are valid both at the beginning and end of the winter season. Although winter velocities are not constant, published GPS records in Southwest Greenland of winter velocities show limited variability (Colgan et al., 2012; van de Wal et al., 2015).

The inversions are run with constant parameters. Both the winter subglacial hydrology run and the subsequent integrated model runs use the same parameters. A parameter search therefore requires ~~an inversion~~ performing the inversion using an effective pressure dependent sliding law for each set of parameters tested.

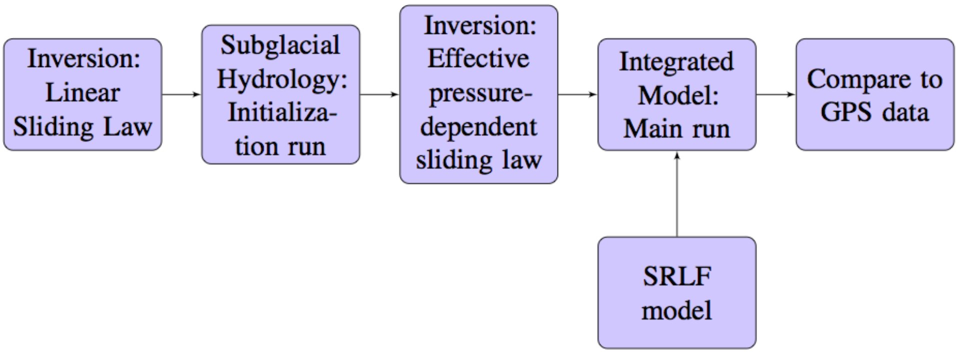

Figure 4. Flow chart showing the work flow for initializing and running the integrated model

2.7 Simulations

We run five main simulations along with those used in the sensitivity analysis (not shown). Two simulations are run calibrating the model using data and inputs for 2009 and 2011. Another simulation is then run validating the model with data and inputs for 2012. Two potential future melt scenarios are simulated by using 2x and 4x the modelled supraglacial input to the subglacial system for 2011. These are referred to as '2011x2' and '2011x4' respectively. The aim of these scenarios is to investigate potential changes in the behavior of the subglacial system, rather than to model a melt season or reliably predict future ice velocities. Accurate predictions of ice velocities would not only require predicted surface runoff, but also depend on predicting changes in ice sheet topography and predicting the future distribution of supraglacial drainage pathways. Addressing these issues requires careful consideration, and is beyond the scope of this paper.

3 Results

3.1 Meltwater input partitioning

The majority of supraglacial meltwater drains into the englacial system (~~Fig. ??~~Table 3), consistent with observations (Zwally et al., 2002; Smith et al., 2015) and previous modelling (Koziol et al., 2017). ~~Hydrofracture~~ Approximately 12% of supraglacial lakes are predicted to hydrofracture. These events drain only a small percentage of surface runoff (1.3%). Most drainage (86.1%) occurs through features modelled as moulins: crevasses, ~~surface to bed~~ surface-to-bed connections subsequent to lake hydrofracture, and moulins outside of lake basins. Of the water drained by crevasses, approximately 30% is generated locally via ablation in crevassed cells, while 70% is routed into crevasses. Water routing into crevasses is concentrated in a small

Pathway	Drainage
Crevasses	24.6%
Moulins	41.8 %
Lake Hydrofracture - Lake	1.3 %
Lake Hydrofracture - Moulin	19.7 %
Lake Storage	0.2 %
Remaining Flow	2.9 %
Lateral Outflow	4.2 %
Ice margin	5.2 %

~~Pie chart of surface~~

Table 3. Surface runoff partitioning into different meltwater pathways for the 2009 melt season in the SRLF domain. Water flowing over the western boundary is categorized as 'Ice Margin', while water flow over the lateral boundaries is labelled as 'Lateral Outflow'. 'Remaining Flow' refers to water still flowing over the ice sheet at the end of the model run. Water flowing into crevasses and moulins are in categories 'Crevasses' and 'Moulins' respectively. 'Lake Storage' refers to water in lakes at the end of the simulation. 'Lake Hydrofracture Lake' refers to the water in lakes that is drained by hydrofracture events themselves. 'Lake Hydrofracture Moulin' refers to water drainage into the subsequent ~~surface to bed~~ surface-to-bed connections from hydrofracture events.

number of cells, with 50% of ~~water routed over the ice sheet~~ the water routed into crevasses entering in only 100 of the 7573 cells forming the perimeter of crevasse fields. Crevasse drainage is concentrated near the ice margin (Figure 5), while drainage into other pathways occurs throughout the study area.

3.2 Calibration

~~Modelled velocities are qualitatively calibrated against~~ Model parameters are calibrated by qualitatively comparing modelled velocities to GPS measurements of horizontal surface velocities from 2009 (Fig 6) and 2011(Fig. 7). The ~~calibration~~ focus of the calibration is on parameters identified as key to determining the morphology of the subglacial system, K_s and σ (Banwell et al., 2016; Hewitt, 2013). The calibration resulted in the two parameters being assigned spatially heterogeneous distributions. The σ field is assigned a background value of 10^{-3}, with 50% of the cells then randomly set to 10^{-4}. The K_s field is constructed using a background value of $10^{-2}\ \mathrm{Pa}^{-1}\mathrm{s}^{-1}$, with 15% of the cell nodes randomly assigned a value of $10^{-7}\ \mathrm{Pa}^{-1}\mathrm{s}^{-1}$. Since K_s is defined on the grid, neighboring nodes are averaged in the x and y directions to determine values on edges. At a sheet depth of 0.1 m, a K_s value of 10^{-2} results in an effective hydraulic conductivity $K_s h^2$ of $10^{-4}\ \mathrm{ms}^{-1}$ (Hewitt, 2013). This is at the upper end of values for till, which are inferred to be 10^{-4} to $10^{-9}\ \mathrm{ms}^{-1}$ (Fountain and Walder, 1998). The secondary value of $10^{-7}\ \mathrm{Pa}^{-1}\mathrm{s}^{-1}$ assigned to K_s was selected to give an effective hydraulic conductivity at the opposite end of the spectrum.

The calibration focused on matching the duration and magnitude of speedup events~~. The~~ , as the timing of the events is controlled by surface input, which was not ~~varied~~sensitivity tested, given we used the same time series of surface runoff for

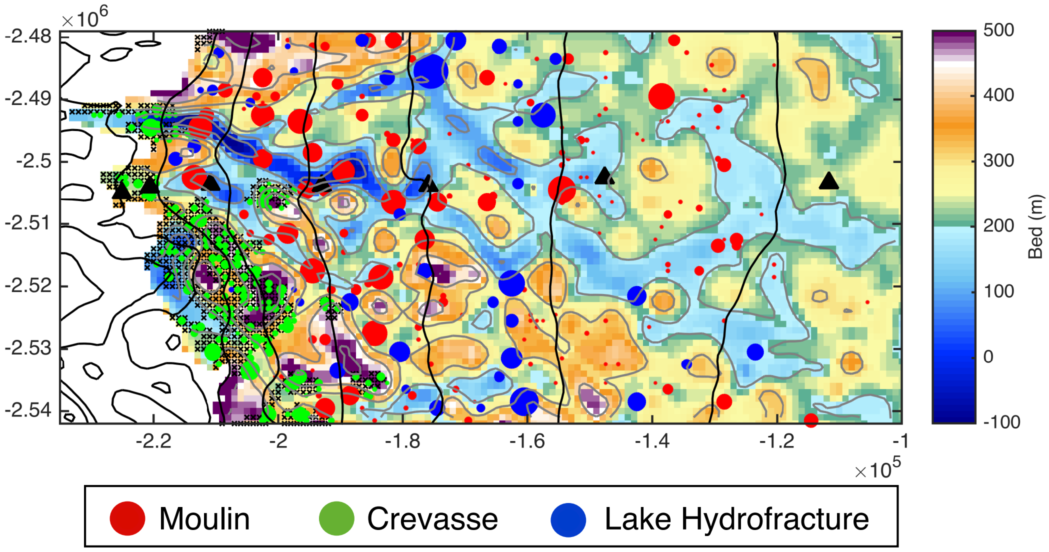

Figure 5. Modelled supraglacial input in the Russell Glacier area for the integrated model domain in 2009. Meltwater pathways are denoted by circles of different colors, with red, green, and blue corresponding to moulins, crevasses, and lakes respectively. Circle areas are scaled by volume. GPS stations are shown as black triangles. Hatch marks show grid cells calculated as crevassed. Crevasse inputs appear within hatched areas due to resampling from 90 m to 1000 m resolution. Background is basal topography from BedMachine2 reinterpolated at 1000 m. Light gray contours correspond to 100 m basal contours. Black lines correspond to 200 m surface topography contours at the same elevations as in Figure 1.

each year from RACMO2.3 in all SRLF runs. The model is calibrated using the ~~Weertman~~ Budd sliding law, and the same parameter values are used in the simulations with the Schoof sliding law. ~~Plots~~ Figures 6 and 7 show model velocities output at noon for the ~~Weertman sliding law~~ Budd sliding law as representative of the daily average, and daily averages calculated from output at 6 hr intervals for the Schoof sliding law. Sub-daily variability in model output is ~~relatively~~ subdued, except during periods of high velocities in simulations ~~applying~~ using the Schoof sliding law (see Koziol (2017)). ~~All model~~ Model output values shown are from the summer immediately following the winter initialization. There are only minor differences between this model output and from running the model for an additional year and using the output from the second summer. Since surface water input to the subglacial hydrological system is a key driver of ice velocities, surface runoff from RACMO2.3 and nearby surface ablation rates determined at weather stations (van de Wal et al., 2015) are plotted alongside velocities. RACMO2.3 surface runoff forces modelled ice flow, while the weather station ablation rate is taken as representative of the water input driving measured ice velocities. Some caution is necessary comparing the datasets, since RACMO2.3 accounts for both refreezing of meltwater and precipitation events. Refreezing, however, should only be a small component (van de Wal et al., 2015). An error of 5% is estimated for the calculated daily ablation rates (van de Wal et al., 2015).

The Schoof and ~~Weertman~~ Budd laws result in model output of comparable fit to the measured velocities for large segments of the velocity time series. However, during periods of high velocities, the Schoof law can overpredict the magnitude of the

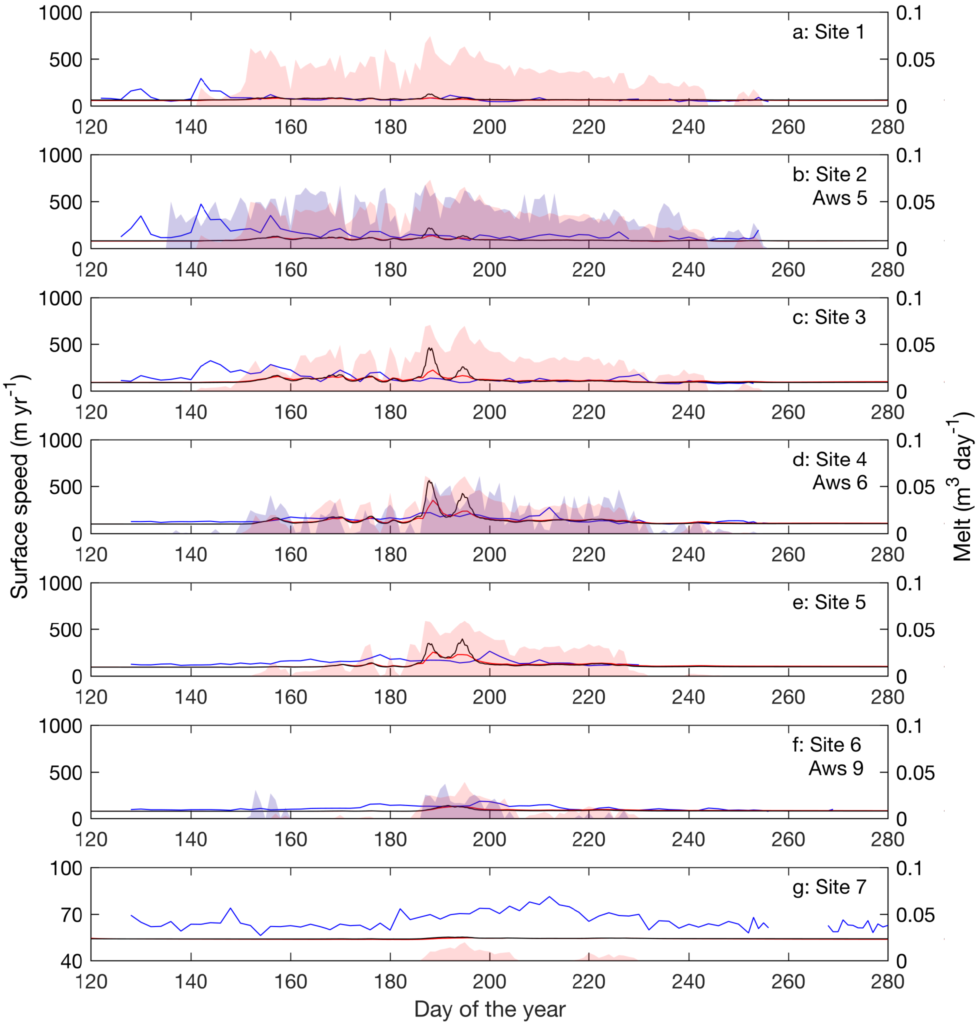

Figure 6. Modelled ice velocities plotted against GPS measurements for the 2009 melt season. Daily average horizontal velocity from GPS measurements are plotted in blue. Modelled velocities using the Schoof sliding law and ~~Weertman~~ Budd sliding law are plotted in black and red respectively. Daily ablation from weather stations are shown in shaded blue, while RACMO2.3 surface runoff is shown in shaded red. Locations of GPS and weather station sites are shown Figure 1. Weather station ablation rates are plotted at the nearest GPS site.

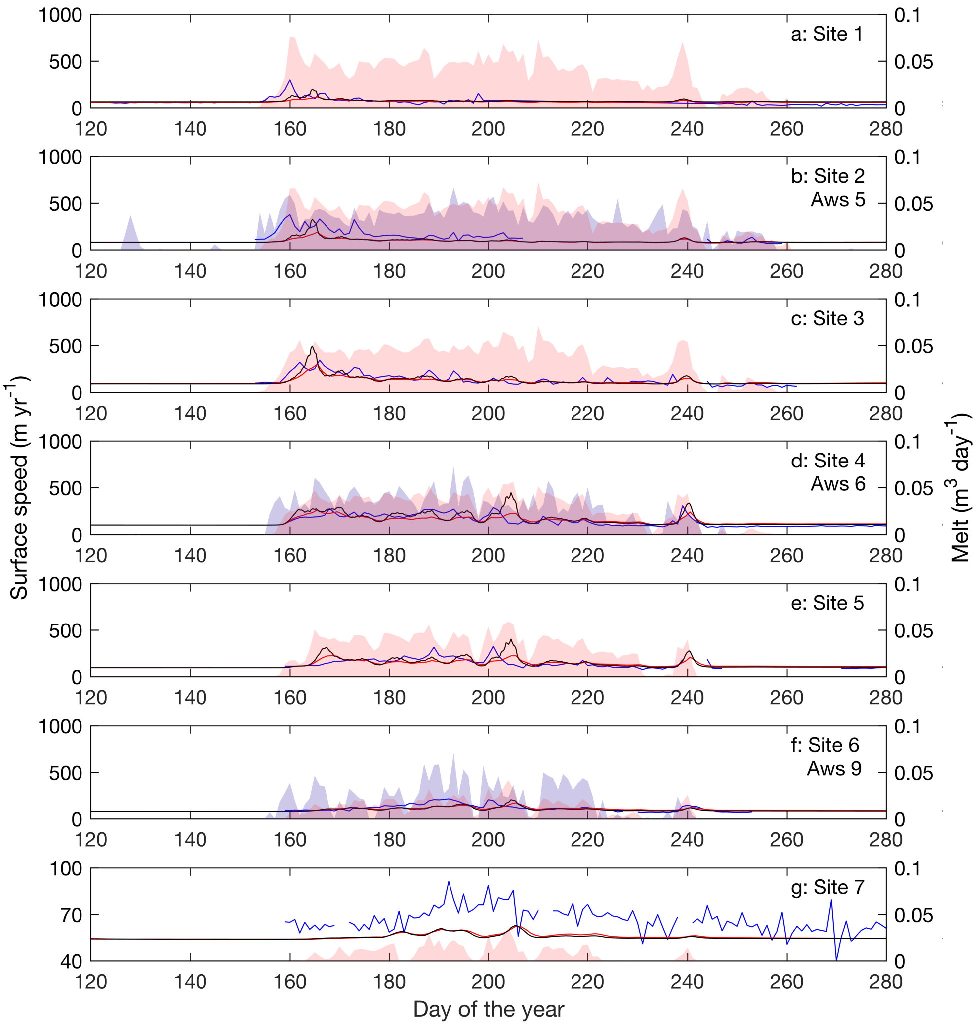

Figure 7. Modelled ice velocities plotted against GPS measurements for the 2011 melt season. Daily average horizontal velocity from GPS measurements are plotted in blue. Modelled velocities using the Schoof sliding law and ~~Weertman~~ Budd sliding law are plotted in black and red respectively. Daily ablation from weather stations are shown in shaded blue, while RACMO2.3 surface runoff is shown in shaded red. Locations of GPS and weather station sites are shown Figure 1. Weather station ablation rates are plotted at the nearest GPS site.

velocity by a factor of 3. Model output with the Schoof sliding law is also observed to have a sharper and higher magnitude summer speedup, as well as a slight increase in velocity variability. Since the ~~Weertman~~ Budd sliding law results in an overall better match to the measured velocities, the analysis of the velocity time series in the remainder of the paper focuses on those results.

~~Near the ice sheet margin, the~~ The model predicts low ice velocities throughout most of the summer melt season at the three GPS sites closest to the margin. In general, measured GPS velocities are also relatively low, except for early season high magnitude variability observed at sites S1-S3 (Figure 6a-c) in 2009, and at sites S1-S2 in 2011 (Figure 7a-b). This observed variability in the GPS velocities precedes melt predicted by RACMO2.3 and is not reproduced by the model. At ~~site~~ sites S1 and S2, modelled velocities show some limited acceleration during the early summer in both 2009 and 2011, ~~similar to the mid-late summer GPS measurements. At site S2, the model under predicts GPS velocitiesin both years~~but to a lesser extent than in the observed velocities. The fit improves at site S3 for both years, as ~~modeled~~ modelled velocities in 2009 approximate ~~summer velocities following early initial summer variability, while~~ observed velocities (after the early onset of increased summer velocity in the observed data), and in 2011 the model ~~also~~ predicts the early summer speedup more effectively.

Modelled velocities at sites S4-S5 (Figure 6d-e and Figure 7d-e) capture the seasonal trend of ice flow, and mirror some of the observed short-term speed-up events. Modelled velocities at S4 match the general flow while diverging from GPS measurements during periods of observed and modelled enhanced flow. In 2011 modelled ice flow shows similar short-term speedup events as the GPS measurements, such as those beginning on days 198 and 237. At site S5, the model does not predict the gradual speedup observed in the GPS velocities. Similar to the GPS measurements, there is a brief period of enhanced flow in mid-summer, followed by a slowdown. In 2011, however, the model captures the early velocity speedup, and the general trend through the remainder of the summer, including the same speedup events observed at site S4.

Model velocities underpredict the measured velocities at the highest sites. In 2009, measured velocities at site S6 (Figure 6f) shows a gradual ~~velocity~~ increase in the first half of the melt season, followed by a gradual decline in the second half. Neither the increase nor decrease in velocity mirrors the weather station ablation rate. In contrast, model velocities are observed to be enhanced in the middle of summer, mirroring modelled melt. Site S6 (Figure 7f) measurements shows faster flow in 2011 than in 2009. The model velocities match the initial velocity increase observed in GPS velocities, but do not reach the same magnitude. A late summer slowdown is observed in both the modelled and measured velocities, as are short-term increases in velocities at days 200 and 240. At site S7, modelled velocities depart from the winter mean by a few meters per year in both 2009 and 2011 (Figure 6g and Figure 7g). Measurements show an increase on the order of 10-20 myr^{-1} in both 2009 and 2011.

In summary, the early summer speedup and subsequent mid summer slow-down at mid-elevations are captured. The model is also able to reproduce the pattern of synchronous speedups observed at multiple adjacent GPS stations. Consistent features not captured are early summer variability at low sites, short term variability, and late summer deceleration below the winter mean. Modelled velocities are only observed to flow slower than the winter velocity mean for a period of a few days and by a small magnitude ($< 5\ \mathrm{myr}^{-1}$).

Ablation rates calculated from automatic weather stations near to sites S2, S4, and S6 are comparable to predicted RACMO2.3 surface runoff. The two data sets show similar magnitude at sites S2 and S4, with higher variability in ablation than runoff. At S6, both ablation and predicted runoff are similar in 2009, while in 2011 ablation is approximately twice the magnitude of surface runoff and has a much higher variability. Qualitatively, model velocities at sites S1-S3 do not correlate to predicted surface runoff, while they do show correlation at sites S4-S6. GPS measurements do not in general show correlation with the ablation rate at S2, and appear only weakly correlated at S4 and S6.

3.3 Model Sensitivity

Calibrating the integrated model is an underdetermined problem. Multiple parameters in each cell across the grid are constrained using only seven times series of point GPS data. The parameters selected for the subglacial hydrological model are not unique in giving a qualitatively good fit. Within the parameter space searched, different sets of parameters either enhanced or dampened the magnitude of the velocity output, or resulted in a velocity signal that significantly diverged from GPS measurements. Extensive sensitivity analysis of the subglacial hydrology component of the integrated model to parameters are conducted in Werder et al. (2013) and Hewitt (2013). In this section ~~, the focus is~~ we focus on the sensitivity of the model to the setup, ~~and the parameters selected to have a spatially heterogeneous distribution~~to K_s, and to σ.

Drainage through crevasses is poorly constrained, and hence the impact of varying crevasse drainage is tested. Velocities at the GPS stations are not found to be sensitive to variations in crevasse drainage. The standard value of the moulin volume threshold of $5 \cdot 10^5\ \mathrm{m}^3$ resulted in crevasse input partitioning into 182 moulins and internal catchments. Changing the threshold value to $10^5\ \mathrm{m}^3$ and $10^6\ \mathrm{m}^3$, resulted in 337 and 122 internal catchments respectively. Model output in both scenarios showed negligible changes. Similarly, neglecting water generated over crevasse fields and only using water flowing into the crevasse fields from external streams had little impact on modelled velocities at the GPS stations.

Lake hydrofracture events result in a large volume of water rapidly draining to the base during the event itself, and a ~~surface to bed~~ surface-to-bed connection which drains water for the remainder of the melt season. The impact of the initial rapid delivery of water ~~was~~ on the model behaviour is tested by running a simulation where the water in the lake when hydrofracture occurs was not input to the base, but removed from the system. The impact on ~~ice velocities~~ modelled ice velocities at GPS stations (none of which are near lakes which undergo hydrofracture) was found to be negligible. The season-long average velocity across the catchment was also not affected.

A ~~variable sheet conductivity~~ heterogeneous sheet flux coefficient field is found to benefit the fit of modelled velocities by increasing the magnitude of the early summer speedup. The results using a constant value of $10^{-2}\ \mathrm{Pa}^{-1}\mathrm{s}^{-1}$ are overall very similar to the ~~calibration~~ calibrated runs, while decreasing the ~~sheet conductivity~~ value to $10^{-3}\ \mathrm{Pa}^{-1}\mathrm{s}^{-1}$ leads to model output with prolonged periods of velocities exceeding 400 myr^{-1}. Increasing the ~~initial coverage of lower conductivity nodes~~ number of grid nodes with the sheet flux coefficient assigned a value of $10^{-7}\ \mathrm{Pa}^{-1}\mathrm{s}^{-1}$ from 15% to 30% had a minor impact. Assigning 50% of the ~~initial~~ grid nodes resulted in a worsening fit early in the summer at site S4, but had little impact at other sites or beyond the initial speedup. Patterning low ~~conductivity~~ value nodes into 4x4 patches, randomly seeded at 125 points was also tested. The number of patches was selected so that if there was no overlap of the patches, 20% of the nodes would be assigned a lower conductivity. Two simulations were conducted with different random locations of patches. One simulation strongly impacted the early summer speedup at site S3 and S4, while the other had a similar effect but on sites S4 and S5.

The GPS records in 2009 and 2011 show differing characteristics, with ice velocities in 2009 showing much less variability and more gradual changes than 2011. The choice of the parameter value setting for englacial storage (σ) attempts to balance the fit in both years. A better fit was observed with increased englacial storage $(\sigma = 10^{-}3)$ for 2009 and ~~less englacial storage~~ decreased englacial storage $(\sigma = 10^{-}4)$ in 2011. Increased capacity of englacial storage had the effect of dampening the velocity output. In 2009, this increased the fit of the model predictions by reducing the high velocities observed at sites S3-S5 between days 180 and 200. However, increased englacial storage also reduced the velocity speedups observed in 2011, particularly around day ~~2015~~205, reducing the fit to GPS measurements.

3.4 Validation

The integrated model is validated against GPS velocity measurements from 2012 (Fig. 8), using the parameter values ~~from the calibrationrun~~determined in the calibration. The pattern of modelled velocities at sites S1 and S2 are similar to those in 2011, with a moderate early velocity speedup followed by a gradual slowdown for the remainder of the summer. Unlike previous years, GPS velocities at site S1 do not exhibit high magnitude velocity variations, improving the match of the modelled velocities. Although the integrated model does not respond strongly to melt input for most of the summer at site S1, it does predict slightly elevated velocities driven by late season input around days 255 and 265, in line with GPS measurements. At site S2, the general pattern of speedup observed in the GPS velocities is mirrored by the modelled velocities. However, the magnitudes are consistently under predicted, particularly those of the short-term high magnitude speedups. The magnitude of modelled velocities improves at site S3 and especially S4, matching the timing but overpredicting the magnitude at S3, and matching both magnitude and timing of events at site S4. Little GPS data is available at sites S5 and S7. Similarly to previous years, model output underpredicts GPS velocities at site S6.

3.5 Increased melt scenarios

The high melt scenarios ~~accelerate the rate of the early summer speedup and result in~~ show faster flow early in the summer and higher peak velocities (Fig. 9). After the early summer speedup at sites S1-S3, simulations 2011, 2011x2, and 2011x4 ~~all predict similar velocities. Modelled velocities can be observed to decrease slightly with increased melt season intensity during periods of slower flow~~ predict broadly similar velocities, although the 2011x2 and 2011x4 runs show slightly lower values overall; this effect can be seen most clearly at site S3. As elevation increases, modelled velocities in the high melt intensity runs decrease more during slow-flow/low melt periods (e.g. days 210-230 at S4). At sites S4-S6, increased melt ~~input~~ intensity results in higher variability of ice flow, with higher peak velocities in the first half of the summer season~~. Modelled velocity is observed to increase with melt input at these sites during the first half of summer~~, but with similar low velocities during low melt periods. The relative increase of peak velocities between 2011x2 and 2011x4 is greater than between 2011 and 2011x2. At ~~sites S4-S6~~ these sites, the model predicts broadly similar velocities in all three simulations for the latter half of summer, from days 210 to ~~238. During this period~~ 238, but at site S4, model velocities ~~decrease with simulation melt input. At~~ are

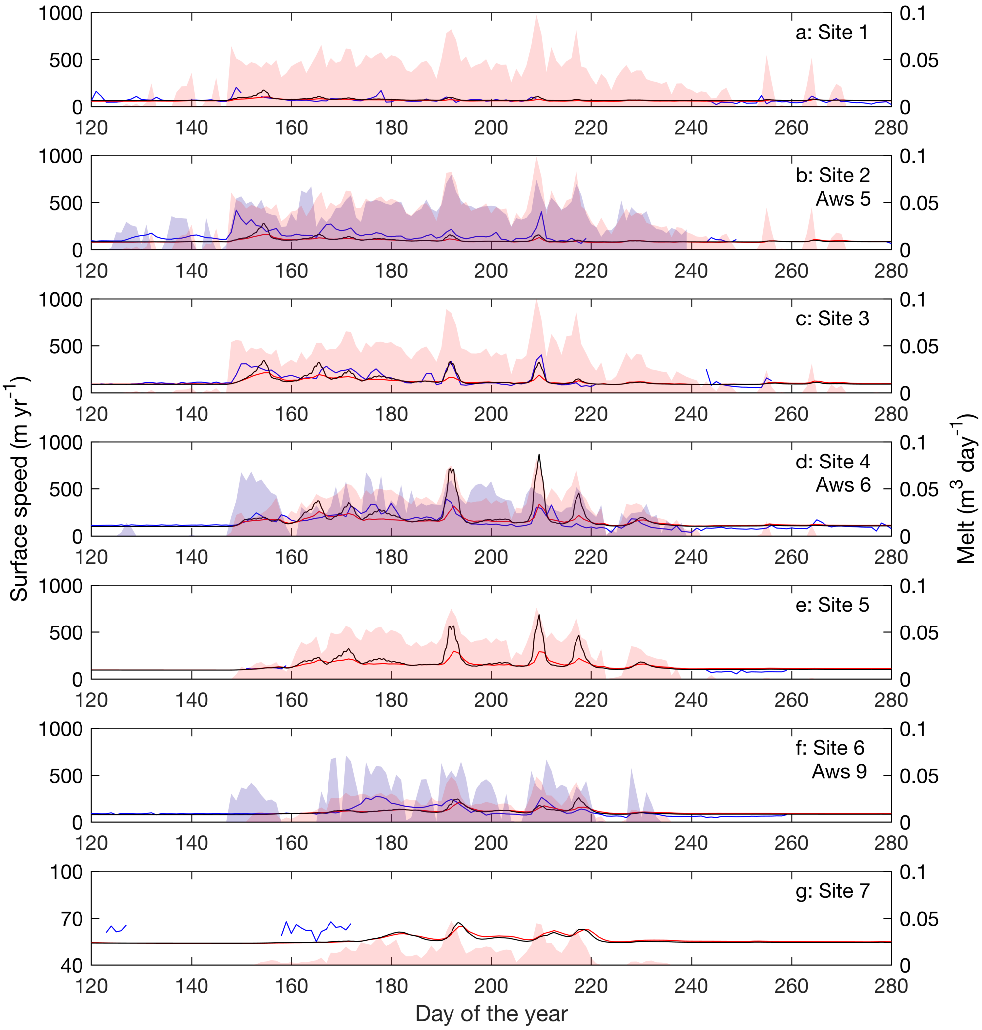

Figure 8. Modelled ice velocities plotted against GPS measurements for the 2012 melt season. Daily average horizontal velocity from GPS measurements are plotted in blue. Modelled velocities using the Schoof sliding law and ~~Weertman~~ Budd sliding law are plotted in black and red respectively. Daily ablation from weather stations are shown in shaded blue, while RACMO2.3 surface runoff is shown in shaded red. Locations of GPS and weather station sites are shown Figure 1. Weather station ablation rates are plotted at the nearest GPS site.

lowest for the 2011x4 scenario, whereas at site S6, modelled velocities increase slightly with greater melt input. Site S5 shows mixed behaviour, with model velocities from simulation 2011x4 higher than the ~~simulation~~ other simulations between days 210 and 222, but lower between days 223 and 236. Between days 210 and 238 at sites S4-S6, model velocities are low and only slightly elevated above their winter values. ~~Starting at day 238, a late season velocity spike is observed, with the magnitude of the velocity increase dependent on melt input.~~ At site S7, the velocities ~~from future simulations are slightly~~ in the increased melt intensity simulations are faster than 2011 velocities~~. The timing of events is similar in all three simulations. As melt input increases, the magnitude of short-term velocity spikes also increases , with a larger increase between 2011x2 and~~ , and with some periods where the 2011x4 ~~than between 2011~~ scenario generates the slowest velocities (e.g. days 198 and ~~2011x2~~210), when short-term melt rates drop after a period of higher melt and velocity. Starting at day 238, a late season velocity spike is observed, most strongly at sites S4 and S5, though apparent at other sites. The melt input during this period decreases with elevation, but the impact of this event increases strongly with elevation to sites 4-5, but then decreases at sites S6 and S7.

3.6 Average Melt Season Velocities

Melt season averaged modelled velocities at the GPS sites are shown in Figure 10. Average velocities are highest at GPS site S4, and decrease towards the ice margin, and at high elevations. Average velocities increase with melt season intensity at all GPS sites, with a pattern skewed away from the ~~ice margin~~sites closest to the ice margin which show the least sensitivity. As melt season intensity increases, velocities in the upper ablation zone and at the equilibrium line (located at 1500 m elevation (van de Wal et al., 2015), slightly above S6) are predicted to increase the most, scaling with melt (comparing 2011, 2011x2, and 2011x4); site S7, with the lowest melt, shows more limited sensitivity. The pattern observed at the GPS stations is generally reflective of that across the study domain (Figure 11)~~. Overall, areas of slow flow are~~ ; areas between around 800m and 1400m show the largest increase, but with areas of slower flow predicted to accelerate more than areas of ~~fast~~ faster flow. Average velocities between 2009 and 2011x4 increase by up to 70%.

3.7 Channel Network Morphology/Extent

The development of the channelized system (see supplementary videos) is similar to that observed in previous modelling studies (e.g Banwell et al., 2016; Hewitt, 2013; Werder et al., 2013) and as inferred from observations (Bartholomew et al., 2011; Chandler et al., 2013). Channelization of the hydrological system begins at the margin and develops progressively up ice-sheet. As channelization develops up-ice, the system evolves to an arborescent morphology. The up-ice extent of channelization increases with summer melt intensity (Figure 12). In 2009, channels occur primarily below the 1000 m surface elevation contour. The extent increases past 1100 m, and approaches 1200 m, in 2012. As melt season intensity increases from 2009 to 2012, pockets of channelization at higher elevations are seen. The maximum extent of channelization occurs at approximately the same time in each modelled melt season, and was qualitatively identified to occur between days 220-225 in all three melt seasons. Although the extent of channelization varies between 2009, 2011, and 2012, there are no significant differences in the organization of the channelized system. In the future scenario 2011x4 the morphology of the channelized system is similar to that in the modelled melt seasons. However, the extent increases further upstream past 1300 m and approaches 1400 m.

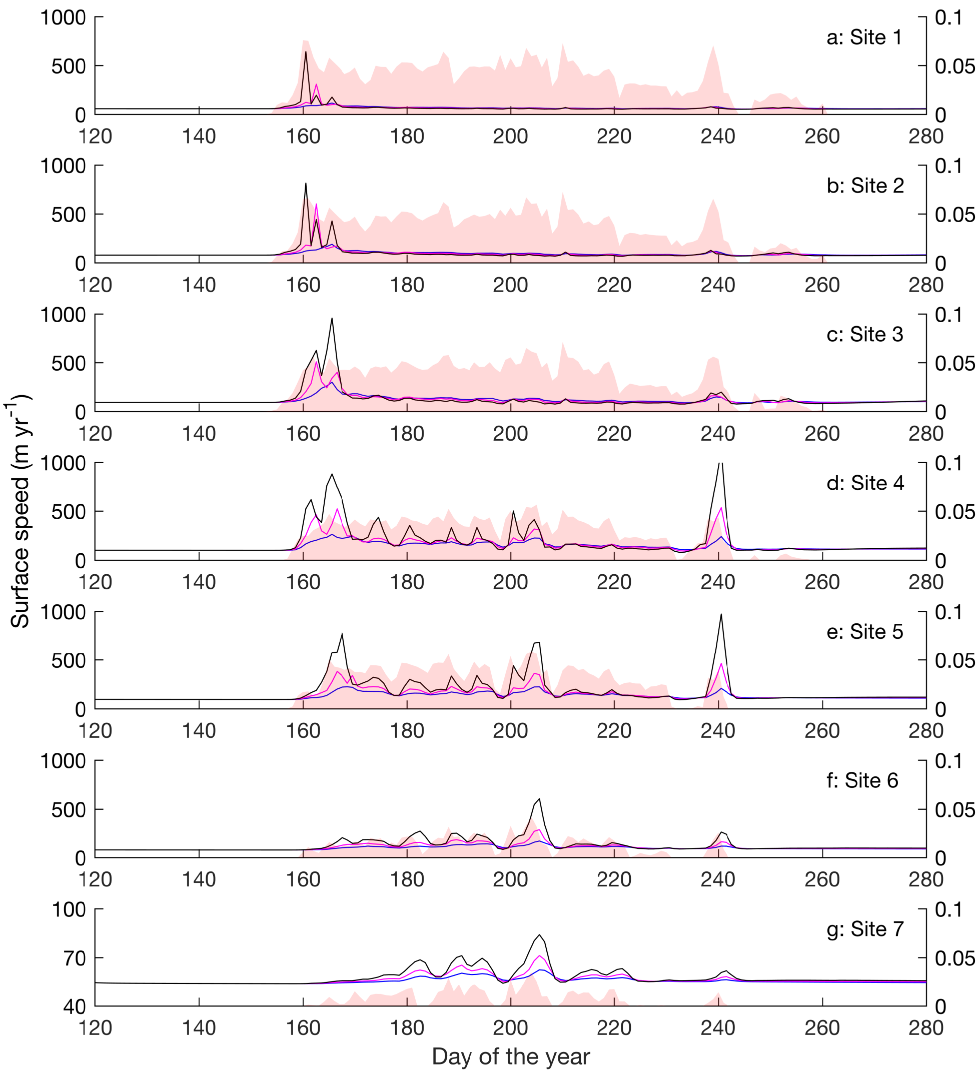

Figure 9. Modelled ice velocities using a ~~Weertman~~ Budd Sliding law plotted for the 2011 melt season (blue), the 2x melt scenario (magenta), and for the 4x melt scenario (black).

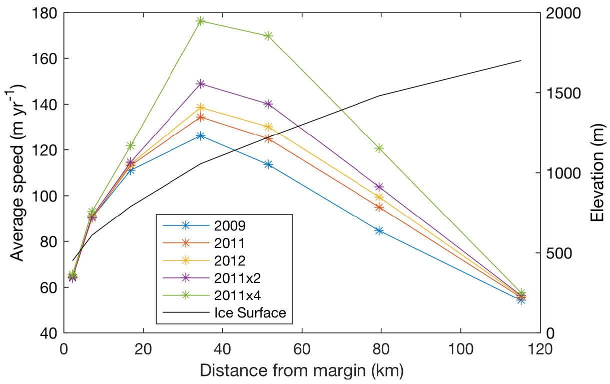

Figure 10. Averaged modelled melt season velocities at each of the GPS sites.

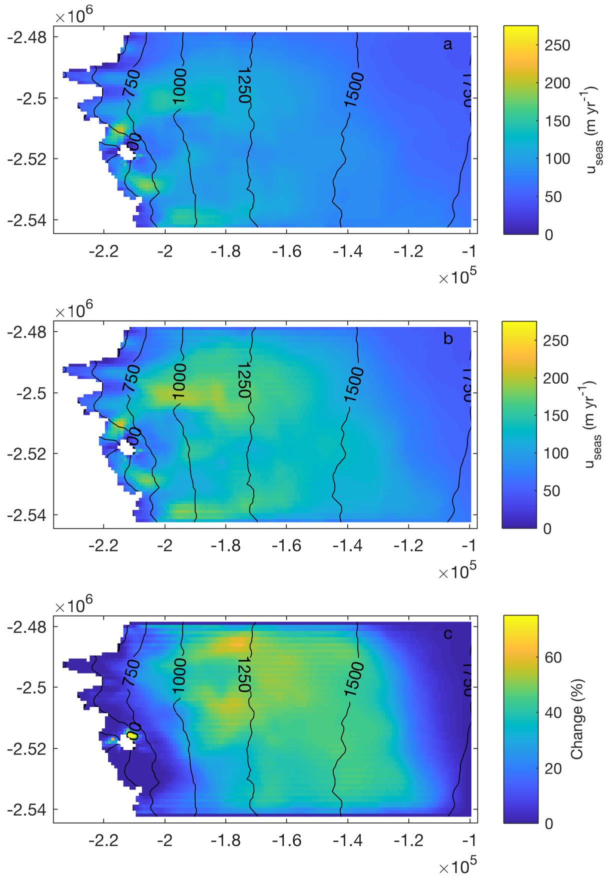

Figure 11. a) Map of melt season average velocities for 2009. b) Map of melt season average velocities for 2011x4. c) Change (%) between the melt season average velocities of 2009 and 2011x4.

Figure 12 shows the locations of moulins used as tracer injections points in Chandler et al. (2013). Dye-tracing experiments by Chandler et al. (2013) were performed in the summers of 2009 to 2011. Except for moulin IS39, tracers injected into the moulins drained from the subglacial system at an outlet located near moulin L1. Tracers injected into IS39 are reported to drain from an outlet of an adjacent catchment. The channel morphology in the modelled melt season output does not predict a major outlet located near L1, nor that L41 and L57 would drain near L1. However, the model does predict that IS39 is on a different branch of the channelized system. Based on tracer measurements in 2011, Chandler et al. (2013) report that channelization extends to at least L41, but not as far as L57. The modelled channelized system during 2009, 2011, and 2012 is inline with that result.

3.8 Distributed and Channelized Discharge

Water flow beneath the ice sheet is modelled to occur in interacting distributed and channelized systems. The discharge in each system follows similar trends for all three modelled melt seasons (Figure 13). In 2009, 2011, and 2012, integrated discharge over the summer melt season in the channelized system is slightly less than half (43%-48%) of the integrated discharge in the distributed system. Modelled discharge begins to increase simultaneously in both systems at the start of the melt season. In 2011 and 2012, discharge in the distributed system rapidly increases in the early melt season. This is followed by a long period with overall high flow but with strong variations. At the end of the melt season, discharge in the distributed system rapidly decreases. In 2009, the early season increase in discharge is less rapid and more prolonged, and discharge peaks before decreasing to a plateau, after which it rapidly decreases. Discharge in the channelized system increases at a much slower rate, and tends to increase until mid-late summer. It mirrors many of the short-time scale variations in the distributed system but with a dampened magnitude. At the end of the melt season, discharge in the distributed system decreases at a higher rate than in the channelized system~~, so that there is~~. In 2011 and 2012, this results in a brief period (after around day 240) in which discharge in channels is higher than in the distributed system. Under the future melt scenario 2011x4, the integrated discharge in the channelized system increases to 77% of the integrated discharge in the distributed system. Early in the melt season, discharge increases in both the channelized system and distributed system simultaneously. Similar to the ~~modelled~~ other melt seasons, discharge in the distributed system increases at a faster rate. However, ~~peak discharge~~ drainage in the channelized system ~~is nearly the same magnitude as peak discharge in the distributed system, and discharge in the channelized system~~ equals or exceeds that of the distributed system much earlier in the year (Day 200).

4 Discussion

4.1 Model Fit

The modelled velocities are the combined result of five models (RACMO2.3, SRLF, an ice sheet model, the associated adjoint model, subglacial hydrology model) and several datasets. Most parameters used in the models are assigned standard values, with calibrated parameter values for the subglacial hydrology model. The validation simulation affirms the calibrated model,

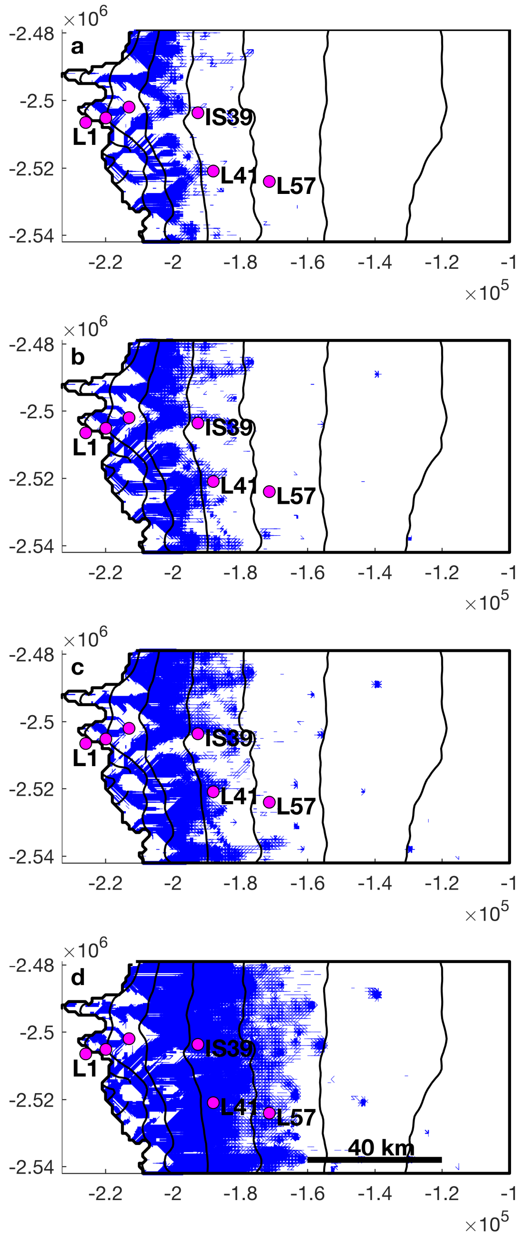

Figure 12. Channelized system at maximum extent: a) 2009. b) 2011. c) 2012. d) 2011x4. Moulin locations used as tracer injections sites in Chandler et al. (2013) are shown in purple. Two moulin locations are unlabeled for clarity. Black lines correspond to 200 m surface topography contours at the same elevations as in Figure 1.

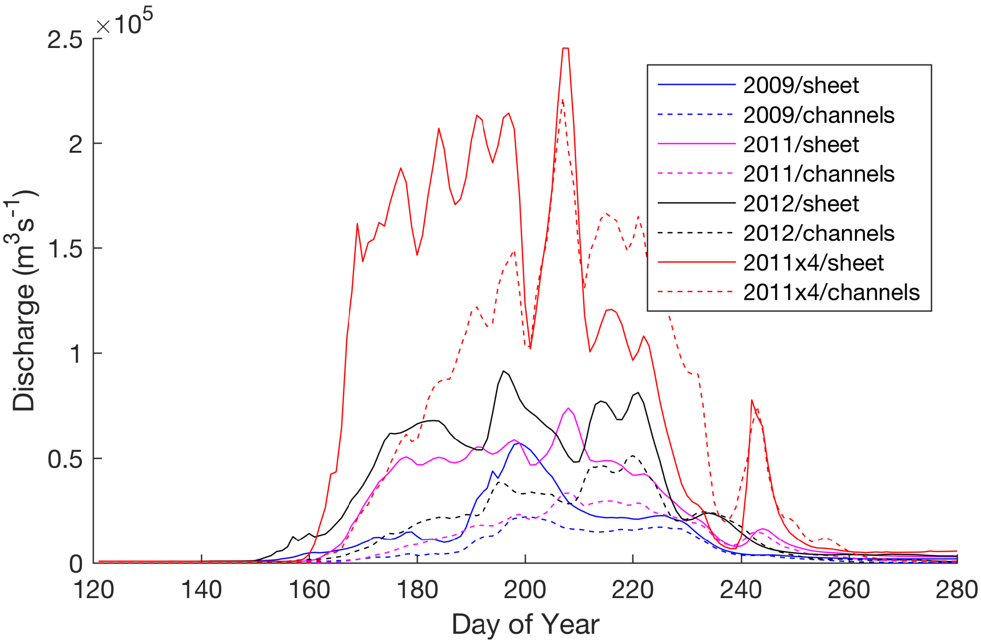

Figure 13. Time series of discharge in the distributed ("sheet") and channelized ("channels") system for the 2009, 2011 and 2012 summers, and the 2011x4 future melt scenario.

as measured velocities are reproduced to the same qualitative level of fit. Although each model has biases and is limited by assumptions, their combined result reproduces measured ice velocities to a first order. Many of the features observed in the GPS time series are captured in the modelled velocities. This gives confidence that the models and datasets are representative of their respective component. The complexity of the models, and the process, makes assigning a model uncertainty infeasible. It is unclear how to partition the cause of model mismatch between: errors in inputs such as topography, model/theoretical uncertainty such as the form of the sliding law, or ~~computational~~ computationally imposed limitations such as grid resolution or choice of ice sheet model.

Overall, model velocities are observed to be better at mid-elevation than either at the lowest or highest sites. Model velocities at sites S1-S2 are likely affected by the model not recreating the subglacial water routing inferred by Chandler et al. (2013). A number of factors could contribute to differences in water routing, including errors in topographic data, the spatial distribution of inputs from crevasse fields, and model assumptions and boundary conditions. In general, thin ice and steep gradients in topography make ice flow and hydrology modelling near the margin difficult. ~~Thin ice deviates from the assumption of a high aspect ratio in the hybrid formulation, while steep gradients are likely to~~ Steep surface gradients may lead to stresses assumed negligible ~~in the~~ by the hybrid formulation in the ice stress balance. Drainage components in the subglacial hydrology model are formulated in terms of effective pressure, on the implicit assumption that they remain full. Underneath thin ice, or when there are steep gradients, both channels and cavities could be expected to exist while partially full or empty. The atmospheric pressure boundary condition prescribed at the ice sheet margin in the subglacial hydrology model, may in reality, extend inland for periods in the summer. Additionally, the high velocity spring/early summer events observed in the GPS records occur before any melt is predicted by RACMO2~~. Similarly~~.3. Similar to the study by Bougamont et al. (2014), modelled velocities do not capture this behavior. These velocity events may be the result of internal dynamics of water stored over winter (Schoof et al., 2014), such as flooding events, that the subglacial hydrology model ~~cannot~~ does not capture, or early season melt which RACMO2.3 does not predict.

Modelled velocities at sites S6-S7 may be affected by excess capacity in the cavity system due to over prediction of basal ice velocities from the inversion process. The inversion process results in a sliding ratio of approximately 0.8 at the high elevations (Koziol and Arnold, 2017). However, internal deformation can be expected to be dominate over basal sliding so far inland, suggesting a much lower sliding ratio. Measurements at boreholes in the Paakitsoq region at lower elevations show a sliding ratio of 0.44-0.73 during the winter, increasing episodically to 0.9 during the summer (Ryser et al., 2014). The largest discrepancy between ablation at a weather stations and RACMO2.3 modelled surface runoff occurs at site S6, likely due to RACMO2.3 allowing for refreezing of surface melt. This additional complexity increases the uncertainty in runoff predictions, and surface input to the base may be underestimated at sites S6 and S7.

The development of the subglacial hydrology system is driven by surface runoff input to the bed, and is a key control on velocities across the domain. Measurements in the Russell Glacier area of a single 63.1 km^2 moulin terminating catchment at approximately 1250 m elevation over a 72 hr period found that RACMO2.3 overestimated runoff by approximately 60% (Smith et al., 2017). In general, an average of multiple regional climate models was reported to overpredict surface runoff by +21% to 58% for the catchment (Smith et al., 2017). The impact of any discrepancies between modelled and actual surface runoff is not necessarily limited to a local temporal and/or local spatial scale. However, to what extent the results of the (Smith et al., 2017) study generalize across the model domain is unresolved.

Spatial maps of modelled velocities show some numerical artifacts. Although these do not appear to have a strong direct impact on the velocities at the GPS stations, numerical artifacts are a cause for concern and should be mitigated in future work. One likely cause is high velocity gradients near the lateral margins due to the Dirichlet boundary conditions. A second is strong variations in basal drag due to subglacial hydrology likely results in non-negligible horizontal gradients in vertical velocities, contrary to the assumptions of the hybrid formulation. Alternative boundary conditions or numerical schemes to improve convergence may mitigate these effects, but were not pursued further in this study.

4.2 Model Sensitivity

Model velocities calculated with the two different sliding laws are comparable during much of the melt season. The timing of events are not ~~effected~~ affected by the choice of sliding law, and the primary difference observed is the magnitude of velocities during short-term speedup events. The overprediction of speedup during events with the Schoof sliding law suggests adding a regularization constant, such that a minimum basal drag exists. Such a term could reflect the fact that the subglacial hydrological system may not extend throughout a gridcell, or that part of the cell has a weakly connected system with a different water pressure (Hoffman et al., 2016). Simulation results shows the ~~Weertman~~ Budd sliding law with standard exponent values has practical value in simulations. However, the form and parameters of the sliding law remain uncertain, and the Schoof law has greater theoretical support (Hewitt, 2013).

Calibrating the integrated model is an underdetermined problem, as the number of observations is not sufficient to constrain the parameters in all the models. The calibration therefore focuses on the key parameters of the subglacial hydrology model, while keeping parameters of the ice sheet model and surface hydrology model constant. The calibration was achieved mainly by trial and error, starting with values used in Hewitt (2013). Most model parameters of the integrated model are similar to previous studies applying the subglacial hydrology model (Hewitt, 2013; Banwell et al., 2016). The most significant parameter value difference is the sheet ~~conductivity~~flux coefficient (K_s). The primary value of 10^{-2} ~~is between the order of magnitudes of 10^0 and~~ $\mathrm{Pa}^{-1}\mathrm{s}^{-1}$ in our study is greater than the value of 10^{-5} ~~used in Hewitt (2013) and Banwell et al. (2016) respectively~~$\mathrm{Pa}^{-1}\mathrm{s}^{-1}$ used in Banwell et al. (2016). The parameter values for the model reported in Banwell et al. (2016), which are calibrated against observed water discharge at an outlet in the Paakitsoq region, were found not to reproduce GPS velocity records, as water at mid-high elevations was not effectively evacuated. The difference in parameters suggests that care needs to be taken transferring parameter values between study sites in different areas and at different scales.

The calibrated value for sheet conductivity is at the higher end of inferred values for till (Fountain and Walder, 1998). Although model results are no longer comparable when sheet conductivity decreases by an order of magnitude, model results are resilient to heterogeneity. The simple tests conducted suggest that random heterogeneity in sheet conductivity has a lower impact than larger-scale spatial patterns. Heterogeneity in sheet conductivity could arise from local topography, variable till coverage, and till properties (including deformational history). A constant ~~sheet~~ bed roughness height scale of 0.5 m is ~~selected as a reasonable value~~ used in this paper. However, patterns of ~~sheet thickness~~ bed roughness would also provide a strong control on discharge at the base. Overall, model results suggest it is necessary for the distributed system to be able to sustain a high discharge.

The initial rapid delivery of a large volume of water to the bed during individual lake hydrofracture events ~~are~~ is not observed to have a ~~pronounced effect in modelled velocities~~ lasting or widespread effect on modelled velocities (in line with observations by Hoffman et al. (2011)). This suggests that lake hydrofracture events in themselves are not a key process in the long term or large scale development of the subglacial hydrological system~~. At~~ , as at lower elevations, the numerous conduits and high water input drive channelization, while at higher elevations, a combination of insufficient input and conditions unfavourable for channelization exist. Rather, the primary impact of lake ~~hydrofacture~~ hydrofracture is in opening surface-to-bed connections~~,~~. The spatial density of such events has been shown to affect the rate of development of channelized drainage (Banwell et al., 2016), and to act as a key mechanism for the creation of moulins away from crevasse fields or current lake basins (Hoffman et al., 2018), which then drain a significant proportion of the overall surface melt as we find in this study, and previous work (Koziol et al., 2017).

The configuration of internal catchments and moulins which drain crevasses was not found to have a strong impact; neither was eliminating drainage of water generated from ablation in internal catchments within crevasse fields. However, the GPS sites at which model velocities are compared do not capture spatial heterogeneity of crevasse drainage, which occurs along the length of the ice margin. Hence, the impact may be much stronger at other locations within in the study area. However, since model velocities at higher GPS sites were not observed to vary with changes in crevasse drainage, the impact of crevasse drainage should be limited to the margin.

4.3 Model Complexity

It is encouraging that the results provide a ~~good match to~~ clear match to many features seen in velocity observations, particularly at the relatively coarse resolution used. However, the models and workflow applied in this paper are characterized by a high degree of complexity. An important consideration is where simplifications can be applied, and where further complexity may be justified.

The use of a higher-order ice sheet model/inversion code should be explored due to increased accuracy in basal velocity calculations. Basal velocities are a key control of the subglacial hydrological system since they determine cavity spacing and provide an important feedback (Hoffman and Price, 2014). A ~~higher order~~ higher-order model may perform more robustly throughout the study area. Areas where the performance of the hybrid model may be expected to be sub-optimal occur throughout the study area. Such areas are characterized by: ~~low~~ high aspect ratio, high variability in basal topography, or low sliding ratio. The ice flow model is also constrained by the assumption of a uniform temperature distribution throughout the ice. Calculating a thermal-mechanical steady state, or alternatively inverting for the structure, would increase accuracy of calculated basal velocities. Either of these options could be incorporated in the step with the linear inversion at limited cost since this step is only executed once. Importantly, both the use of a higher order ice sheet model and determination of the thermal state can be implemented without adding further assumptions or unconstrained parameters.

The subglacial hydrology model is the least constrained model in the workflow. Many parameters remain unknown and the exploration of its behavior is limited by the parameter space searched. However, a key behavior not replicated is the late summer/fall slowdown, and subsequent gradual winter acceleration. The integrated model returns to its initial state at the end of summer. This indicates a need for a component of the model which operates on a longer timescale than is currently included. The difficulty in recreating both the smoother 2009 velocity record and the more variable 2011 record also suggests inter-annual variability in the background state of the hydrological system. A model component simulating weakly connected regions of the hydrological system as incorporated in Hoffman et al. (2016) may be key to reproducing these observations. These regions are conceptualized as parts of the distributed system with a much lower hydraulic connectivity. The connectivity of these regions may be temporally variable.

The SRLF model offers the best opportunity for simplification. To at least a first order, lakes which hydrofracture can be modelled as moulins (in line with observations by Hoffman et al. (2011)). This suggests using the locations of moulins derived from satellite imagery acquired at the end of the melt season as representative of both moulins outside of lake basins, and hydrofractured lakes. Lake hydrofracture events are observed to result in temporarily faster ~~flow locally~~ local flow (Stevens et al., 2015; Tedesco et al., 2013). In order for a model to capture these events, the specific location, timing, and volume of lakes will need to incorporated into the model. Given the ongoing uncertainties around the processes controlling hydrofracture, this ~~implies~~ suggests that using observational records of lake drainages derived from satellite imagery (as in Bougamont et al. (2014)) to derive hydrofracture input to the ice-bed interface forms a valid strategy for present-day studies, though such an approach would not work for prognostic tests. Crevasses also drain a significant proportion of water, most of which travels over the ice surface into crevasse fields from upstream, rather than being generated locally. The controls on water drainage through crevasses to the ice sheet bed are poorly understood, but may have an important role as the spatial density of water inputs are known to influence the development of the subglacial hydrological system (Banwell et al., 2016). Since moulins and crevasses drain water in a continuous manner with a high spatial density, a simpler surface hydrology scheme approximating input into each drainage pathway from its local catchment may be effective. The output of each catchment into the corresponding drainage pathway may be simplified to two output hydrographs, one for snow-covered and the other for bare-ice conditions. For internal catchments of crevasse fields routing can likely be neglected. This calculation need only be done once; moulin input at each time step could then be calculated at little computational cost based on total surface runoff and the dominant surface cover in the catchment.

4.4 Implications

The ~~success of the model in recreating features in the measured velocitiesprovides validation for each model component, as well as their integration. The work supports integrating models of high complexity, incorporating a range of processes. Further model refinement and data acquisition should continue to improve the fit between modelled and measured velocities. A key uncertainty in the initialization process was the subglacial hydrology model run during winter, and the subsequent inversion for background basal parameters. Although the process used cannot capture year on year changes, the practical value of the initialization process is implicitly validated through the subsequent fit to measured velocities. The model results also support the hypothesis that the margin of the GrIS is controlled by subglacial hydrology in a manner similar to alpine glaciers~~existence of channelized and distributed systems beneath the GrIS is inferred indirectly through borehole observations, dye tracing experiments, and patterns of GPS velocities, building on extensive observations and theoretical developments derived from studies on alpine glaciers. The key result of this paper is to provide numerical support for the understanding of subglacial hydrology of the GrIS, based on theories derived from studies of alpine glaciers, as well support for the explicit description of the model components we include (i.e. the equations used). We show that these theories can quantitatively reproduce measurements to a first order, and in the sense of our validation, predict ice velocities. This builds on previous work which shows that this understanding can be used to reproduce idealized seasonal patterns of ice velocity (Pimentel and Flowers, 2010; Colgan et al., 2012; Hewitt, 2013), as well as effective pressures in line with ice velocities (Werder et al., 2013; de Fleurian et al., 2016).

The timing of velocity variations are controlled by surface input and modulated by subglacial hydrology. At high elevations where channelization is not observed, variations in model velocities track modelled surface runoff closely. GPS velocities, however, do not show the same fidelity to the time series of ablation from automatic weather stations, which are qualitatively more variable than modelled runoff. This suggests dampening of the variability of surface input by the supraglacial and subglacial hydrology, and that variability in daily ablation rates are not simply correlated to faster flow. A quantitative analysis of the two time series may provide better insight into the relationship between surface melt and ice velocities. However ice velocities are driven by the cumulative melt over a larger upstream area from the point of measurement, which may not be well represented by the variability of melt at a single point. At lower elevations, channelization is important in modulating the impact of surface water on ice velocities. The low modelled and observed velocities closer to the ice-margin imply a consistently high effective pressure at the GPS sites, due to the impact of channelization on water pressures and water routing.

Modelling predicts that average summer ice velocities over the melt season will increase with melt season intensity. A similar correlation was observed in GPS records over the upper ablation zone of the Russell Glacier region by ~~(van de Wal et al., 2015)~~ van de Wal et al. (2015), but not in GPS records at North Lake, Western Greenland by Stevens et al. (2016). This implies that more intense melt seasons will result in a higher ice flux towards the margin during the summer. Whether this would be ~~offset~~ compensated for in terms of the average annual ice velocity by decreased ice flux during the winter is unresolved by the model.

Channelization is observed to develop more extensively and further inland as melt intensity increases. This trend is observed in the three modelled melt seasons, and continues into the two future melt scenarios. This suggest that the subglacial hydrological system will continue to drain surface meltwater input in a similar manner as melt intensity increases beyond 2012 levels. Since channelization is thought to result in the observed slowdown in mid-late summer (Tedstone et al., 2015; van de Wal et al., 2015), and is also postulated to result in slowdown in the subsequent winter and spring (Sole et al., 2013; Tedstone et al., 2015; van de Wal et al., 2015), model results suggest increasing summer melt intensity ~~should~~ could lead to a more spatially extensive annual velocity slowdown. The slowdown may also become more pronounced in the future as the channelized system is predicted to drain an increased proportion of water, and accesses a larger proportion of the model domain.

However, ~~model results show average summer velocitiesscaling with melt season intensity at mid-elevations. The modelled change in summer velocity at GPS~~ as channelization increases up-ice in our model, we do not see a marked impact on model velocities. Model velocities at the higher GPS stations in model runs 2011x2 and 2011x4 both show a similar pattern to 2011, with a higher magnitude of ice flow during speedup events. We do not observe a shift in velocity patterns towards that of lower GPS stations, with acceleration early in the melt season transitioning to deceleration in the latter part of the melt season. This suggests that channelization may have a more limited impact on annual velocities in the accumulation zone. The magnitude of any impact is unresolved by our model. In particular, although there are periods when velocities in the 2011x4 run are lower than 2011x2 and 2011, the magnitude of this decrease is bounded. This is a limitation of the model, which is only able to decrease velocities nominally below the initial winter values. This also has the consequence that we are unable to model the winter season accurately.

The key question for the longer term response of the ice sheet to increased melt is whether the potential summer increase in velocity due to increased melt will outweigh any late summer and winter decrease due to the evolution of a more efficient system under higher melt conditions. While observations show long-term decreases in ice velocities in the lower ablation zone (Stevens et al., 2016; Tedstone et al., 2015; van de Wal et al., 2015), this question remains unresolved at higher elevations. Although we cannot directly predict annual velocities with the model presented in this study, we can investigate how annual velocities may change at the limits of winter behaviour.

One limit of winter velocities is that integrated ice flow over the winter decreases faster than integrated ice flow over the summer. This is observed in GPS measurements in the upper ablation zone in the Russell Glacier region by van de Wal et al. (2015) . Under this limit, channelization has a similar impact at high elevations as in the ablation zone. Velocity measurements near the vicinity of a lake hydrofracture at approximately 1450 m elevation suggest that channelization occurs even at high elevations

(Bartholomew et al., 2012; Nienow et al., 2017). Winter velocities in this limit will decrease until they hit a lower bound where flow is purely deformational, with no contribution from basal sliding. The maximum increase in mean summer velocities is approximately 60 $\mathrm{m\,yr^{-1}}$, at GPS stations 4 and 5 between the 2009 and 2011x4 melt scenarios~~is around 60~~. Assuming a winter velocity of 100 $\mathrm{m\,yr^{-1}}$ and an ~~8~~ 7 month-long winter, ~~this increase would offset a~~ the summer increase predicted by the model would compensate for a possible reduction in winter velocity to around 60 $\mathrm{m\,yr^{-1}}$. This approaches the lower bound for winter velocity suggested by borehole measurements showing that internal deformation accounts for 25-50% of the total ice velocity in the Paakitsoq region of western Greenland (Ryser et al., 2014). Climate model predictions suggest surface runoff rates ~~quadrapuling~~ quadrupling from present levels circa 2100 (Shannon et al., 2013; Van Angelen et al., 2013).

The second limit occurs if winter velocities at higher elevations are not impacted by channelization, and summer velocities dominate the annual signal. Arguments that thick ice and shallow surface slopes inhibit channel growth at high elevations favour this limit of behaviour (Meierbachtol et al., 2013; Dow et al., 2014), as do observations suggesting limited changes in the efficiency of the channelized system (Andrews et al., 2014). Under this scenario, a change of mean summer velocity of 110 $\mathrm{m\,yr^{-1}}$ to 170 $\mathrm{m\,yr^{-1}}$ with winter velocities remaining constant at 100 $\mathrm{m\,yr^{-1}}$ would result in mean annual velocities increasing from 104 $\mathrm{m\,yr^{-1}}$ to 129 $\mathrm{m\,yr^{-1}}$ between the 2009 and 2011x4 simulations. Under this scenario, annual velocities would increase by approximately 25% by approximately 2100, when surface runoff is predicted to quadruple.

Interpreting the model velocity output from the future melt scenarios is difficult ~~.~~ however, and our bounds should be interpreted cautiously. We do not evolve our model geometry, nor evolve the distribution of surface drainage locations, nor use climate model predictions of surface runoff for the future. As melt season intensity increases, the validity of the initialization and calibration parameters also becomes more uncertain. Further, the model has bias towards capturing short-term speedup events, rather than prolonged slowdowns due to model velocities remaining near or above their winter values. The modelled velocities show higher variability, and a significant increase in the magnitude of short-term speedup events. However, quantifying whether ~~these will be offset~~ the impact of these events on annual velocity will be compensated for by a corresponding late summer slowdown or by a winter slowdown is beyond the capability of the current model. Model output can be interpreted to suggest that a late summer velocity slowdown ~~offsetting~~ compensating for an early summer speedup is less likely at higher elevations. It is not evident, however, whether the suggested upper bound of a 25% increase in annual velocities in this limit would have an impact on the overall mass budget of the ice sheet as great as that from a 4x increase in surface runoff in itself.

The success of the model in recreating features in the measured velocities provides validation for each model component, as well as their integration. The work supports integrating models of high complexity, incorporating a range of processes. Further model refinement and data acquisition should continue to improve the fit between modelled and measured velocities. A key uncertainty in the initialization process was the subglacial hydrology model run during winter, and the subsequent inversion for background basal parameters. Although the process used cannot capture year on year changes, the practical value of the initialization process is implicitly validated through the subsequent fit to measured velocities.

5 Conclusions

In this paper, ~~multiple models are coordinated~~ we couple multiple models in order to predict summer ice velocities at the southwest margin of ~~GriS~~ GrIS from topographic and climatic input data. These models represent the main components of the ice sheet system: supraglacial hydrology, subglacial hydrology, and ice flow. The key component of the simulations presented in this paper is a coupled hydrology-ice flow model. This integrated model is initialized using a workflow incorporating the adjoint ice flow model, and is forced during the simulations using surface input from a surface hydrology model. Calibration of the integrated model takes advantage of GPS velocities from two summer melt seasons: 2009 and 2011. The model validation on 2012 GPS data reproduces measured ice velocities to a similar degree as in 2009 and 2011. To a first order, the magnitude and timing of the measured velocities are replicated in modelled velocities at multiple sites.

The success of the multicomponent modeling to recreate summer velocities reflects on the integrity of each individual model and dataset. This work should encourage further model coupling as it suggests that individual components and datasets are robust. However, limitations of the multicomponent model are evident in the model output, particularly that the model velocity does not significantly drop below ~~it's~~ its initialized winter value. Additional data and theory will be necessary to address these issues. Together, the models also form a quantitative test of the hypothesis proposed by numerous authors ~~(e.g Chandler et al., 2013; Cowton et al., 2013; Colgan et al., 2011; Hewitt, 2013; Hoffman et al., 2011; Schoof, 2010; van de Wal et al., 2~~ (e.g Chandler et al., 2013; Cowton et al., 2013; Colgan et al., 2011; Hewitt, 2013; Hoffman et al., 2011; Schoof, 2010; van de Wal et al., 2 that the summer acceleration of the GrIS margin is controlled by the evolution of the subglacial hydrological system in a manner ~~analagous~~ analogous to the seasonal speedup of alpine glaciers. The key result of this paper is quantitative support in favour of this hypothesis.

The observed decadal-timescale slowdown at the margin of the GrIS is attributed to increased channelization reducing late summer and winter water pressures (Stevens et al., 2015; Tedstone et al., 2015; van de Wal et al., 2015), and hence velocities. Our results suggest that the decadal slowdown will continue in the near future, ~~but the~~ particularly closer to the ice margin. However, the model predicts a strong scaling of the average summer velocity ~~may diminish this trend next century. This suggests that a better understanding of~~ with melt season intensity. We investigate the impact of this under two limits. If integrated ice flow over the winter decreases faster than integrated ice flow over the summer at higher elevations, our modelling suggests that annual velocities in the ~~controls on future reductions in ice sheet flow in fall and winter will be important for improving prognostic models of the ice sheet response to climate forcing.~~ upper ablation zone would begin to increase by around 2100 (when surface runoff is predicted to quadruple from present levels), as predicted summer velocity increases offset likely winter velocity decreases. In the second limit we investigate, where winter velocities remain at present levels while summer velocities increase, our model suggests an upper bound of a 25% increase in annual velocities by around 2100.

Competing interests. The authors declare no competing interests

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