March 5, 2020

Dear Editor Elizabeth Bagshaw,

Thank you for your letter on February 13 inviting revisions to our manuscript, ***"Inter-comparison of surface meltwater routing models for the Greenland Ice Sheet and influence on subglacial effective pressures."*** We are pleased to state that we have complied with all of the requests made by you and the two reviewers. A stepwise, detailed response to all comments is as follows:

Handling Editor:

Thank you for your comments to the reviewers. They note that the paper is a valuable contribution to the field, and I encourage you to take into account their recommendations in your preparation of the revised article.

In particular, please address:

1. Overuse of acronyms, particularly in the abstract and subheadings

2. Readability of the figures. I note that even in the revised versions some of the titles are superimposed.

3. Framing of the study for a glaciology audience

4. Boundary conditions.

Reply: Thanks for your comment. We have: (1) deleted most acronyms in the abstract and subheadings (p. 1); (2) revised the superimposed titles in Figures 2, 4, and S1-S4 (p. 24-26); (3) better explained the three surface meltwater routing methods, making the study more useful and readable for a glaciology audience (p. 4, lines 2-15; p. 5, lines 13-31; p. 6, lines 1-16; p. 7, lines 1-13; p. 8, lines 2-8); and (4) rerun the subglacial hydrology simulations with a more realistic downstream boundary condition (p. 9, lines 5-16; p. 10, lines 16-32; p. 11, lines 1-32), as requested.

Reviewer #1:

General comments: This study focuses on different ways of treating the supraglacial drainage of water at the surface of ice sheets. The region of interest studied here is Russell Glacier in South West Greenland. The authors presents an inter-comparison of three different surface routing models and compare their results to the output of a Regional Climate Model (RCM). The different inputs are further compared through by using them as the forcing quantity provided to a subglacial drainage model. The conclusion of the study are that the use of a supraglacial drainage system allows to get a better representations of the lag of the water input to the moulins. Some sensitivity among models also allow to quantify the impact of the

Digital Elevation Model resolution on the drainage characteristics.

1. ("This study provides an interesting insight into the differences that arise from the use of different supraglacial drainage model. However, my impression is that this study should be further refined in order to be more understandable and provide a usable tool for the community. I find that the presentation of the different models and their results is lacking detail and clarity. Moreover I am concerned by the choice that were made with regards to the boundary condition that are applied to the subglacial hydrology model. Details of my concerns and potential improvement are given bellow section by section.")

Reply: Thanks for the comment. We have: (1) reorganized the results and the discussion sections to make the study more understandable; (2) better clarified the three surface meltwater routing models in the methods and data section (p. 4, lines 2-15; p. 5, lines 13-31; p. 6, lines 1-16; p. 7, lines 1-13; p. 8, lines 2-8); (3) rerun the subglacial hydrology simulations with a more realistic downstream boundary condition (p. 9, lines 5-16; p. 10, lines 16-32; p. 11, lines 1-32); (4) revised the main figures of this study to make them more readable (p. 24-28); and (5) published all the model codes online (https://doi.org/10.6084/m9.figshare.11635932.v1). We think the revised manuscript is much easier to follow and the three routing models will be usable tools for the community.

2. ("1.1 Abstract: The abstract is quite hard to read due to the accumulation of acronyms. Where possible I would urge the authors to refrain from using acronyms in this part of the papers. It might be beneficial to simplify the abstract to make it more accessible to readers which might afterwards gather the details of the study in the rest of the paper. As an example, the author could state that they compare three surface meltwater routing models at this point 1 without specifying those models, the list of variables line 21 (page 1) could be omitted and replaced by "key variables".)

Reply: We have simplified the abstract, as requested (p. 1, lines 14-33; p. 2, lines 1-6). Most acronyms have been deleted. We suggest that the full names of the three routing models are necessary because they are used to explain the results. The revised abstract is as follows:

"Each summer, large volumes of surface meltwater flow over the Greenland Ice Sheet surface and drain through moulins to the ice sheet bed, and impact subglacial hydrology and ice flow dynamics. Runoff modulations, or routing delays due to ice sheet surface conditions, propagate to englacial and subglacial hydrologic systems and require accurate assessment to correctly estimate subglacial effective pressures and short-term lags between surface meltwater production and ice motion. This study compares hourly supraglacial moulin discharge simulations from three surface meltwater routing models, (1) synthetic unit hydrograph, (2) surface routing and lake filling, and (3) rescaled width function, for four internally drained catchments located on the southwestern Greenland ice sheet surface. Using surface runoff from the Modèle Atmosphérique Régionale regional climate model (RCM), simulated variables used for surface meltwater routing are compared among the three routing models. For each catchment, simulated moulin hydrographs are used as input to the SHAKTI subglacial hydrologic model to produce corresponding subglacial effective pressure variations in the vicinity of a single moulin. Two routing models, surface routing and lake filling and rescaled width function, which require the use of a digital elevation model

(DEM), are assessed for the impact of DEM spatial resolution on simulated moulin hydrographs. Surface routing and lake filling is sensitive to DEM spatial resolution, whereas rescaled width function is not. Our results indicate the three surface meltwater routing models perform differently in simulating moulin peak discharge and time to peak, with rescaled width function simulating later, smaller peak moulin discharges than synthetic unit hydrograph or surface routing and lake filling. We also demonstrate that the seasonal evolution of supraglacial stream/river networks can be readily accommodated by rescaled width function but not synthetic unit hydrograph or surface routing and lake filling models. Overall, all three models produce more realistic supraglacial discharges than simply using RCM runoff outputs without an applied routing scheme; however, there are significant differences in supraglacial discharge generated by the three models tested. This variability among surface meltwater routing models is reflected in SHAKTI subglacial hydrology simulations, which yield substantially different diurnal effective pressure amplitudes depending on the applied surface meltwater routing model; however, display relatively consistent mean effective pressure across routing models."

3. ("1.2 Introduction: The introduction gives a succinct outlook on the motivations of the study. This could be developed further to point out the current lack of representation of the supraglacial drainage system and the necessity to have a better representation of this system. The description starting on line 20 (page 2) would be better in a method section of the paper. Moreover, some terms defined in the introduction (such as Unit Hydrograph or Internally Drained Catchments) might not be familiar to the Cryosphere community and the author should consider defining those in more details.")

Reply: The current lack of representation of the surface meltwater routing leads to an insufficient understanding of surface-to-bed meltwater connections and ice dynamics, as the reviewer pointed out. Additional new text has been added to better highlight this point, as requested (p. 2, lines 28-30).

The definitions of Unit Hydrograph and Internally Drained Catchments have been added, as requested (p. 2, lines 19-20; p. 3, lines 3-4). Internally drained catchments (IDCs) are "hydrologic units on the GrIS surface that collect and drain meltwater through supraglacial stream/river networks to terminal moulins or lakes" (Yang and Smith, 2016). Unit hydrograph (UH) is "a transfer function that is widely used for modeling catchment runoff response to rainfall events for some unit duration and unit depth of effective water input" (Smith et al., 2017). A new section has been added to better define unit hydrograph in more details, as requested (p. 5, lines 13-23).

The description starting on line 20 (page 2) introduces the three routing models and their different assumptions and data requirements. We suggest that it may be useful to explain these three models clearly in the introduction section.

4. ("I don't completely agree with the statement starting on line 10 (page 2) to my knowledge supraglacial meltwater routing is usually simplified in subglacial hydrology models (e.g. Banwell et al., 2016; de Fleurian et al., 2016) it would be interesting to have

some citation here that present studies directly using an RCM as their water input. I am not sure that the citation to Flowers et al. (2018) is relevant in this context or I missed the point of the author here. Further down, the citation to Bartholomew et al. (2011) seemed to be misplaced here as this specific study treats about observations rather than modelling.”)

Reply: Flowers (2018) is a review of Greenland hydrology, which discusses some important issues in surface-to-bed meltwater connection. We agree with the reviewer that Flowers (2018) may not be appropriate to state that “surface meltwater routing is either simplified or simply ignored” so it has been deleted, as requested (p. 2, line 18). Reviewer 2 made the same comment. We agree that Bartholomew et al. (2011) is primarily “about observations” so have removed this citation (p. 2, line 21). We have listed several studies (see Table S1) that use RCM runoff as water input, as requested.

5. (“1.3 Study area and data source: This section is missing a major information as the study area is actually never named. The Russell glacier region will be familiar to most of the reader interested of the subject but mention of it should still appear in the paper. My opinion is that this section should be merged into a section 3 (Methods and Data). Regarding the content of the present section it is not clear to me how and why the IDCs that are presented in this section were generated and why those specific IDCs have been chosen.”)

Reply: Section 2 (Study area and data sources) has been merged into Section 3 (Methods and Data) as suggested (p. 4, line 19). The Russell Glacier region has been added to better introduce the study area, as requested (p. 4, lines 20-24).

We have better explained the reasons to select the four IDCs, as requested: “They are distributed at approximately 200 m elevation intervals in order to span the elevational range of most well-developed IDCs found in the Russell Glacier region and the variable surface melt conditions of this region. Large supraglacial lakes are absent in these four IDCs and surface meltwater is all routed to the moulin at the catchment outlet. As such, surface runoff produced in each IDC should equal to the moulin discharge. A moulin discharge hydrograph collected at Rio Behar catchment (IDC2 in this study; 67.049346N, 49.025809W) for 72 h from 20 to 23 July 2015 was used to calibrate parameters of SUH and RWF models (see Sections 2.5 and 2.6). It is problematic to apply these empirically-derived parameters over large spaces and long times (Yang et al., 2018). Therefore, the selected IDCs are distributed in a relatively small region and the areas of IDC1, IDC3, and IDC4 are similar to the Rio Behar catchment (IDC2)”, as requested (p. 4, lines 23-31).

6. (“1.4 Methods: The description of the different models here is quite brief and some more details could be provided. Particularly it would be interesting to have a better overview of the advantages and drawbacks of each models. The paragraph starting line 15 (page 5) would fit better in the introduction of the study rather than here. Subsections 3.5 and 3.6 refer to the sensitivity studies that where performed for some of the model, it could be beneficial to transfer those sections into the descriptions of the relevant models. That would outline the advantages and potential drawbacks of the models and would clarify the overall setup of the experiments.”)

Reply: Overview of the advantages and drawbacks of each model has been provided in the introduction section and a new table (Table S1) has been added to better compare the three routing models. RWF can mimic seasonal evolution of supraglacial stream/river networks by varying the partitioning of hillslope versus open-channel zones. SRLF, in contrast, assumes the bare ice surface has a stable response to the surface melt and uses static meltwater routing velocities to build the UH. SUH relies on C_p and C_t to build the UH. If we can have a moulin hydrograph during the entire melt season, we can calculate multi-temporal C_p and C_t using variable time-to-peak (t_p), peak discharge (h_p), and main-stem stream length (L), thus creating multi-temporal UHs. Unfortunately, we do not have such measurements at present so SUH cannot mimic variable hydrologic response of a catchment to surface melt.

Table S1. A brief summarization of surface meltwater routing models.

Model	Meltwater Routing	Applicable on bare ice surfaces		Applicable on snow surfaces	Parameter dependency	DEM dependency	Case study
		Hillslope	Open-Channel				
Instantaneous RCM runoff	No	-	-	Yes	No	No	(McGrath et al., 2011; Bartholomew et al., 2012; Rennermalm et al., 2013; Fitzpatrick et al., 2014)
Snyder Synthetic Unit Hydrograph (SUH)	Yes	-	-	Yes, but model parameters should be recalibrated	C_p, C_t are calibrated using a field-measured moulin hydrograph	No	(Smith et al., 2017)
Surface Routing and Lake Filling (SRLF)	Yes	No	Yes	Yes	No	DEM is required to calculate meltwater flow velocities for all catchment cells	(Arnold et al., 1998; Willis et al., 2002; Banwell et al., 2012; Banwell et al., 2013; Arnold et al., 2014; Banwell et al., 2016; de Fleurian et al., 2016; Koziol and Arnold, 2018)
Rescaled Width Function (RWF)	Yes	Yes	Yes	Yes, but model parameters should be recalibrated	Hillslope and open-channel flow velocities (v_h and v_c) are calibrated using a field-measured moulin hydrograph	High-resolution (<10 m) DEM is required to calculate hillslope flow path length	(Yang et al., 2018)

Moreover, SUH and RWF both rely on several empirically parameters (C_p and C_t for SUH, and v_h and v_c for RWF) calibrated from a moulin hydrograph measured at the Rio Behar catchment, southwest GrIS during a very short time period (72 hours), July 2015 (Smith et al., 2017). In contrast, SRLF is more solid and applicable over large spaces and long times. because it only relies on DEM to calculate meltwater flow velocities (Banwell et al., 2012). In this study, we assume these empirically parameters are transferable over space and time but this assumption needs further validation. It may hold for ice sheet surface with similar hydrologic and glaciological environments but is problematic to apply over large regions and long times due to evolving ice surface characteristics. Multiple independent, long-term moulin hydrographs will help eliminate the need for this assumption. We have further illustrated the advantages and drawbacks of these routing models through the manuscript (p. 6, lines 3-6; p. 7, lines 9-12; p. 8, lines 2-8; p. 14, lines 6-13).

The paragraph starting line 15 (page 5) has been removed to the introduction section, as requested (p. 4, lines 6-15).

Subsections 3.5 and 3.6 are not sensitivity studies as the reviewer suggested. In contrast, they are both important topics in terrestrial hydrology and this study attempts to expand these two topics to ice sheet hydrology. Zhang and Montgomery (1994) is a classic study investigating the impact of DEM spatial resolution on terrestrial stream flow and we followed their method to investigate the impact of DEM spatial resolution on surface meltwater routing. The temporal evolution of stream/river networks on stream flow is a state-of-the-art topic and attracts growing attention in terrestrial hydrology. For example, a recent study shows that the extension and retraction of the terrestrial stream network can substantially change the mean travel time and the shape of the travel time distribution (van Meerveld et al., 2019), similar to the finding of our study. Therefore, we suggest that these analyses are partially independent of routing models and should have their own subsections. We have better explained the importance of these two sections (p. 12, lines 15-19; p. 13, lines 7-9; p. 16, lines 9-12).

7. ("From the references that were provided in the paper regarding the SRLF model I understand that this model is routing water with different equations if it sits on snow or on bare ice. From the model description given here it seems that only the bare ice formulation was used. Is that so? If yes the reasons for this choice should be explained.")

Reply: Yes, only the bare ice formulation of the SRLF model was used. The parameters of SUH and RWF routing models were calibrated using field-measured moulin discharge on bare ice (Smith et al., 2017; Yang et al., 2018). Therefore, to make these meltwater routing models comparable, we only discussed the situation of meltwater routing on the bare ice surface. This point has been better explained in the revised manuscript, as requested (p. 6, lines 10-16).

8. ("As stated above my main concern with this study is the way in which the subglacial hydrology model is set-up. In my opinion the boundary condition that is given for the left edge of the domain is not realistic, I do not think that we expect to find water pressure at the atmospheric pressure anywhere under the ice sheet. A more sensible choice would be to set the water pressure at a given fraction of the overburden pressure. A change of boundary condition would need to perform new simulations but I would expect a good argumentation on the choice of the present boundary condition if it is to be kept. I also do not understand why the slopes of the bed and surface, and velocities are not taken from the values of the IDCs as is done for the ice thickness. As it stands now I have a hard time trusting the results from the subglacial hydrology model as it seems that the downstream boundary that is currently set is exerting an important control on the whole domain. I would also note that the Figure 2 related to this section is not very informative and could probably be omitted.")

Reply: Thank you for the recommendation to use a more realistic boundary condition for the moulin input-forced subglacial hydrology simulations in the interior of the ice sheet. We have rerun all SHAKTI simulations using a downstream boundary condition with water pressure corresponding to 50% of ice overburden pressure. The new simulations also use mean surface slope calculated for each catchment drainage (used for both surface and bed slopes, maintaining a uniform slab of ice for the 1 km square domain), as well as sliding velocity corresponding to 100% of the mean annual observed surface velocity in each drainage catchment. The mean slopes and surface velocities are included in Table S2. Figure 2 was originally included to show the model discretization and clearly indicates the moulin location at the bed, but we have removed it, as suggested. We have revised "Section 2.9 Subglacial hydrology modelling" and "3.2 Simulations of subglacial effective pressure" to better explain the methods and results of subglacial hydrology simulations (p. 8, lines 22-33; p. 9, lines 1-16; p. 10, lines 16-32; p. 11, lines 1-32).

Table S2. Summary of four study catchments.

<table>
<tr><th colspan="2">Catchment ID</th><th>IDC1</th><th>IDC2</th><th>IDC3</th><th>IDC4</th></tr>
<tr><td colspan="2">Area (km^2)</td><td>53.0</td><td>66.9</td><td>57.3</td><td>58.5</td></tr>
<tr><td colspan="2">Mean Elevation (m)</td><td>1054</td><td>1248</td><td>1473</td><td>1646</td></tr>
<tr><td colspan="2">Mean surface slope (m/m)</td><td>0.018</td><td>0.020</td><td>0.008</td><td>0.008</td></tr>
<tr><td colspan="2">Mean bed elevation (m)</td><td>207</td><td>309</td><td>247</td><td>222</td></tr>
<tr><td colspan="2">Mean bed slope (m/m)</td><td>0.050</td><td>0.075</td><td>0.036</td><td>0.022</td></tr>
<tr><td colspan="2">Mean ice thickness (m)</td><td>847</td><td>939</td><td>1226</td><td>1424</td></tr>
<tr><td colspan="2">Mean ice flow velocity (m/a)</td><td>116</td><td>99</td><td>98</td><td>73</td></tr>
<tr><td colspan="2">Distance to ice edge (km)</td><td>25</td><td>40</td><td>70</td><td>100</td></tr>
<tr><td rowspan="4">Peak discharge time</td><td>RCM</td><td>13-15</td><td>13-15</td><td>13-14</td><td>13-14</td></tr>
<tr><td>SUH</td><td>19-20</td><td>20-21</td><td>19-20</td><td>19-20</td></tr>
<tr><td>SRLF
2m, 5m, 10m,
30m, 90m</td><td>18-19, 20-21,
21-22, 22-23,
22-23</td><td>18-19, 19-20,
21-22, 21-22,
21-22</td><td>17-18, 18-19,
20-21, 22-23,
22-23</td><td>17-18, 19-20,
23, 23, 23</td></tr>
<tr><td>RWF</td><td>22-23</td><td>21-22</td><td>20-21</td><td>21-22</td></tr>
</table>

9. ("1.5 Results: In general I find the presentation of the results quite hard to follow. This might come from the structure that was chosen by the author, from the presentation of the figures or both. I also wonder why only the results from IDC 1 are presented, it appears from the supplementary figures that the results from the four IDCs are quite similar but this should be stated. I also expect that changing the boundary conditions and parameters of the subglacial hydrology model may alter those results. Regarding the presentation of the results, it would be clearer to me if the author would describe first the results of the inter-comparison itself before delving into the sensitivity studies that were performed on DEM resolution and the value of Ac. Comparing the results to a given reference might also help with the clarity of the text.")

Reply: The structure of the results section has been reorganized, as requested. The revised results section includes: 4.1 Simulations of supraglacial moulin discharge, 4.2 Simulations of subglacial effective pressure, 4.3 Long-term evolution of moulin discharge simulations, and 4.4 Effects of DEM spatial resolution on surface meltwater routing. The sub-sections of discussion have been changed accordingly. We agree with the reviewer that the new structure is much easier to follow. The results from the four IDCs are quite similar as the reviewer pointed out. We have explicitly stated this point: "The three UHs (i.e., SUH, SRLF UH, and RWF UH) and their routed moulin discharges for the four IDCs are presented in the supplement; the resultant patterns of moulin hydrographs are similar so we use IDC1 to illustrate our results here", as requested (p. 10, lines 2-5).

As you might expect, the modifications to the subglacial hydrology simulations to include the more realistic boundary condition, surface slopes, and sliding velocities do change the magnitude of the resulting effective pressures (now lower than with the atmospheric pressure boundary condition used in the initial submission). The text has been updated to describe the new results, and the overall behavior and findings of the study remain consistent (p. 8, lines 22-33; p. 9, lines 1-16; p. 10, lines 16-32; p. 11, lines 1-32).

10. ("I generally find the presented figures a bit too busy and so hard to read. Figure 3 is described a lot throughout the manuscript but the size of some panels make it hard to read. As for the text having specific figures for the inter-comparison and the sensitivity study might help to lighten the figures. Figure 4, 6 and 7 however are not described in the Results part and should be included there.")

Reply: To make Figure 3 more readable, we have taken the third column (subglacial effective pressure) and put it in its own figure, as it is a distinct part of the results and discussion (Figures S1 and S2). We have made Figure 3 larger and reshaped the width ratio between the first column (UH) and the second column (moulin discharge) from 1:1 to 1:1.5 to better represent the diurnal moulin discharge (Figure S1). We have added a title "DEM resolution" to Figure 3c and 3e, and a title "A_c" to Figure 3g, changed the x-axis labels of Figure 3e and 3g into "RWF UH (A_c = 100 m^2) and "RWF UH (2 m DEM), respectively, and added legend "RCM runoff" to Figure 3b, 3d, and 3f to make the figure easy to follow. Figure 4 has been removed as suggested. Figures 6 and 7 have been updated and better explained in the main text, as requested (Figures S3 and S4).

Moreover, we cannot obtain the "optimal simulations for SRLF and RWF" because determining DEM spatial resolutions or cumulative area thresholds are important topics in surface hydrology rather than sensitivity analysis (see our reply to your comment 6). Therefore, we prefer to plot variable simulations together and believe necessary legends make all the sub-figures understandable. However, we agree with the reviewer that a less busy figure will be easier to follow. Therefore, we only plot simulation results using 2 m DEM in Figure S4.

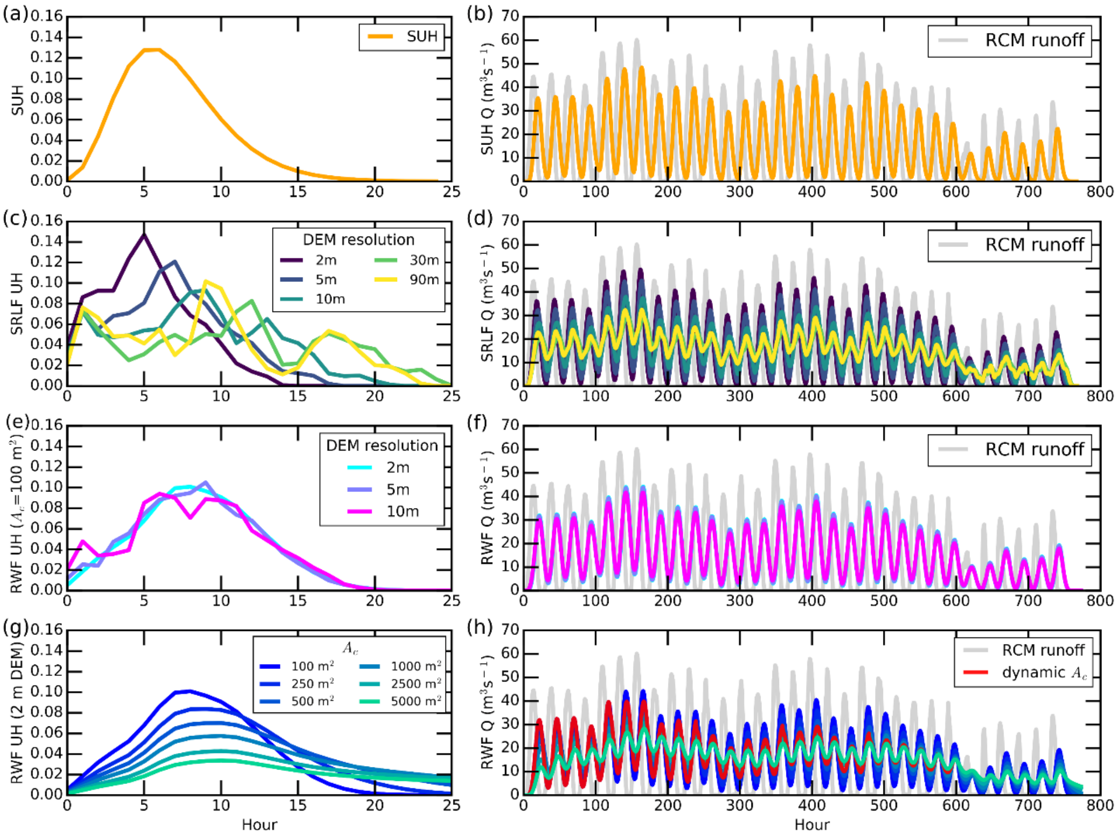

Figure S1. Presentation of Unit Hydrographs (UHs) (column 1) and moulin discharges (column 2) of IDC1 during July 2015, as simulated by three supraglacial routing models (SUH, SRLF, and RWF). A_c is the cumulative contributing area required to initiate a supraglacial meltwater channel and dynamic A_c values are used as proxy for time to simulate the temporal evolution of supraglacial stream/river networks. Simultaneous RCM runoff (grey line) is shown to indicate the effect of surface meltwater routing process on moulin discharge.

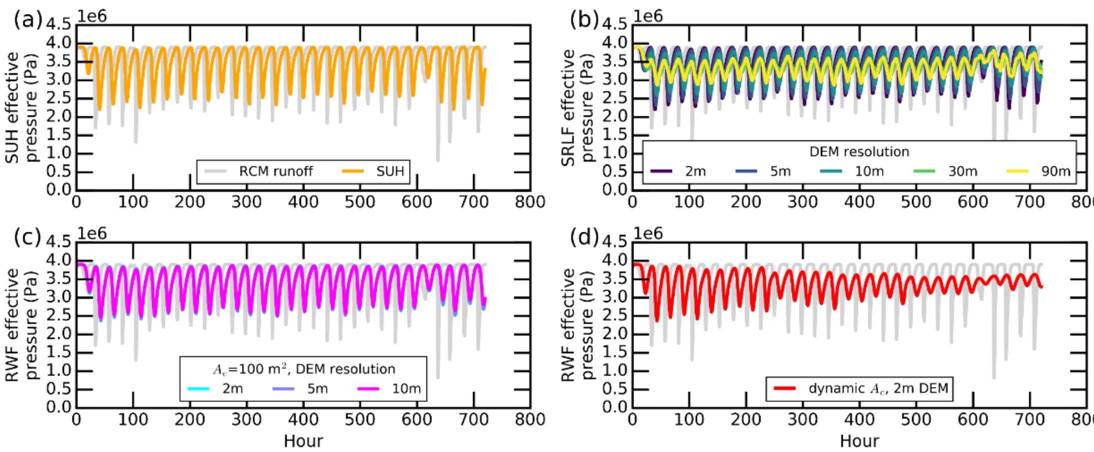

Figure S2. Effective pressures for IDC1 simulated by SHAKTI, with inputs to the subglacial system via a single moulin prescribed by the moulin discharges (shown in Figure S1) calculated by the various routing models. The effective pressure shown here is the spatial mean for the entire 1-km square domain which contains the moulin input at its center.

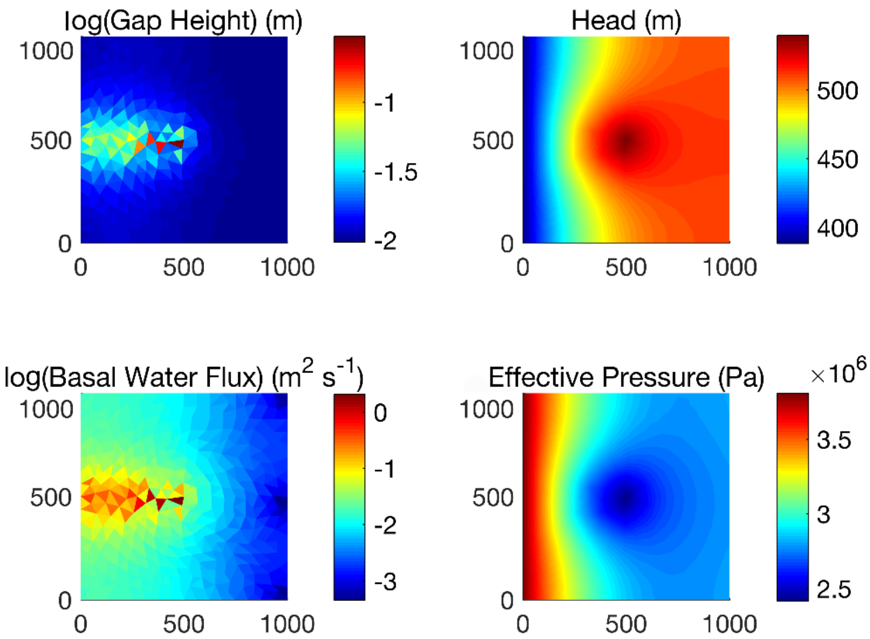

Figure S3. Snapshots of subglacial hydrology fields on day 23 in IDC1 using the SUH routing method to drive moulin input (see full animation of channel evolution and fluctuation in the supplement). An efficient channelized drainage pathway develops from the moulin location at the center of the domain to the outflow at the left, characterized by higher gap height, water flux, effective pressure, and lower hydraulic head than its surroundings perpendicular to flow.

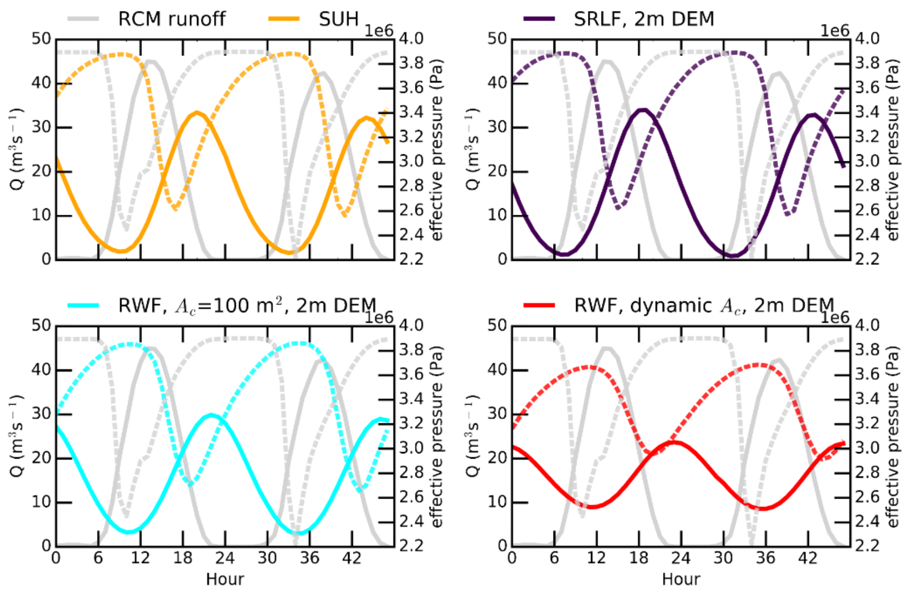

Figure S4. The average two-day cycle of moulin discharge (Q) for IDC1 during July 2015. The daily minimum input in supraglacial moulin discharge (solid lines) corresponds generally to maximum effective pressure (dashed lines), and is followed within 8-9 hours by the daily minimum effective pressure (maximum subglacial water pressure). This suggests that the system shuts down due to creep with low meltwater input, and becomes highly pressurized as meltwater input increases again. As the new water inputs are accommodated, efficient pathways reform and effective pressure increases (subglacial water pressure decreases).

11. (“Lastly I have not seen any information with regard to the sampling of the effective pressure that is discussed, is it an average value or this value is taken at a specific point?”)

Reply: The effective pressure that was described in the initial submission corresponded to the value at the moulin location on the bed (i.e. the head of the channel that forms to the downstream boundary). This description may have been inadvertently removed in the initial manuscript submission (our apologies). In the revised manuscript, we have altered the figures and discussion to focus instead on the mean effective pressure for the entire domain. While the spatial mean effective pressure variations are not as dramatic as seen at the moulin location itself, we feel this gives a more informative view of effective pressure behavior in the vicinity of a moulin, which is potentially more useful from an application perspective.

12. (“1.6 Discussion and Conclusion: The discussion of the manuscript is clear, it would however take advantage of the alterations suggested above for the Result section. Particularly describing all the figure in more details in the result section would help during the discussion. I also expect that the changes required above regarding the subglacial hydrology model might have a significant impact on the results and should be taken into account in the discussion.”)

Reply: The discussion section has been reorganized, as requested. The revised discussion section includes: 5.1 Implications of surface meltwater routing method inter-comparison, 5.2 Influence on diurnal subglacial pressure variations, 5.3 Influence of seasonal supraglacial drainage evolution on meltwater routing, 5.4 Impact of DEM resolution on supraglacial meltwater routing, and 5.5 Future research directions of surface-to-bed meltwater connection. We have better described all the figures in the results section, as requested (see our reply to your comment 10).

As described above, the subglacial hydrology simulations have been rerun with more appropriate/realistic boundary conditions, slopes, and sliding velocities. As noted, these changes do influence the magnitude of resulting effective pressures, but not the overall behavior and differences between routing methods. The text has been updated to reflect the new results (p. 10, lines 16-32; p. 11, lines 1-32).

13. (“I have noted a few minor concern on this section which are listed in the Specific comments bellow. Specific comments. Below is a list of more specific comments throughout the manuscript given with line and page number: Page 1, Line 16: “ice surface” can be replaced by “ice sheet surface”.”)

Reply: Changed as requested (p. 1, line 16).

14. (“Line 17: “climatological melt” should be replaced by “surface meltwater”.”)

Reply: Changed as requested (p. 1, lines 17-18).

15. ("Line 21: MAR abbreviation is not defined here.")

Reply: MAR has been replaced by "Modèle Atmosphérique Régionale" (p. 1, line 21).

16. ("Line 23: "input" can be replaced by "used as input"")

Reply: Changed as requested (p. 1, line 24).

17. ("Page 2, Line 2: Surface melt is not restricted to the ablation zone but occur in the accumulation zone too.")

Reply: "across the ablation zone of" has been replaced by "on" (p. 2, line 8).

18. ("Line 3: "Greenland ice surface" should be "Greenland ice sheet")

Reply: Changed as requested (p. 2, line 9).

19. ("Line 3: "can be" should be "is"")

Reply: Changed as requested (p. 2, line 10).

20. ("Line 14: Bartholomew et al. (2011) does not seem to be a fitting citation here as this paper treats of observations.")

Reply: Bartholomew et al. (2011) has been deleted, as requested (p. 2, line 21).

21. ("Page 3, Line 3: "to discern", to is missing")

Reply: "to" has been added, as requested (p. 3, line 19).

22. ("Page 4, Line 13: The parameters Cp and Ct should be explained.")

Reply: C_p and C_t are two parameters depending on "units and drainage-basin characteristics". This has been explained, as requested (p. 5, lines 28-29).

23. ("Line 13: "time-to-peak in" reads strangely.")

Reply: "in" has been deleted (p. 5, line 28).

24. ("Line 15: I am not sure that the citations are needed here an interested reader will find those in Smith et al. (2017)")

Reply: These two citations have been deleted, as requested (p. 5, line 31).

25. (“Page 5, Equation 2: t; tc and th are not described in the text.”)

Reply: t_h is the hillslope travel time and t_c is the channel travel time. This has been explained, as requested (p. 7, line 2).

26. (“Line 16: Replace “research” by “study”.”)

Reply: Changed as requested (p. 4, line 8).

27. (“Page 6, Line 6: The contributing area (Ac) should be introduced and discussed in the model description.”)

Reply: Cumulative contributing area (A_c) defines the surface area needed to initiate open channel flow. Larger A_c values will yield smaller open-channel zones because larger contributing interfluve areas are required to form open channels. Additional new text has been added to explain A_c, as requested (p. 8, lines 15-16, 20-21).

28. (“Line 15: “compute” rather than “derive”.”)

Reply: Changed as requested (p. 8, line 24).

29. (“Line 19: “framework” could be omitted.”)

Reply: Changed as requested (p. 8, line 29).

30. (“Page 7, Line 6: “climate model” can be skipped here.”)

Reply: Changed as requested (p. 9, line 20).

31. (“Line 7: The times given here do not agree with the one that are present on Figure 3. The author should choose which are the more relevant and keep them throughout.”)

Reply: The peak discharge time 13:00-15:00 is shown in Table 2 rather than Figure 3. This point has been better explained, as requested (p. 9, line 22).

32. (“Line 16: I don't agree with the statement on the smoothness of the UHs. From the figure it seems that the UHs from SUH are actually the smoothest of all.”)

Reply: We mean the RWF UH is flatter than SUH and 2 m SRLF UH because its peak UH value is smallest, thus distributing surface meltwater more ‘smoothly’ over time. We now think this is confusing as the reviewer pointed out so we have changed this sentence into “The peak values of RWF UHs are smaller than SUHs and 2 m SRLF UHs therefore RWF UHs temporally distribute surface meltwater most smoothly”, as requested (p. 10, lines 4-5).

33. (“Page 8, Line 2: Shouldn't it be “potential dynamism”?”)

Reply: Changed as requested (p. 12, line 5).

34. (“Page 9, Line 16: Figure 7 actually shows the results from the three different models not only SUH. The comparison between the results of SHAKTI with the forcing from the RCM and the various models should be presented here to convince the reader of the advantage to use those models. As stated before, the setup of the subglacial hydrology model should be corrected to give convincing results. I am also unsure of the location where the effective pressure presented on Figure 7 is sampled from the model.”)

Reply: In the original manuscript, the effective pressure was sampled from the location on the bed where the meltwater is input (i.e. the “moulin location” on the bed). Similar behavior is seen by examination of the mean effective pressure instead, however, and we have altered the revised manuscript to focus on this quantity (see our reply to your comment 11).

35. (“Line 30: The study from Chandler et al. (2013) actually shows subglacial travel time. I don't see how this reference fits here.”)

Reply: Chandler et al. (2013) focused on subglacial travel time, as the reviewer pointed out but also reported peak supraglacial river discharge time for an IDC at southwest GrIS (moulin site L41 in their study) during 29 June to 7 July 2011. Thereby, we suggest that this reference fits here.

36. (“Page 10, Line 18: Should be “bare ice”.”)

Reply: Changed as requested (p. 16, line 16).

37. (“Figure 2: I don't think that Figure 2 is necessary and it could be skipped.”)

Reply: Figure 2 has been deleted, as requested.

38. (“Figure 3: This figure is quite hard to read as it holds a lot of information. I would suggest to plot on this figure only the optimal simulations for SRLF and RWF which would allow an easier and more fair inter-comparison of the models. Another solution might be to split the figure to present the inter-comparison on a specific figure and the sensitivity studies on others. Finally, a zoom on some relevant period for the discharge and effective pressure would help the comparison of the different models. I also noticed a discrepancy here between the times given in the first column and the one of the text. It would be advantageous to introduce the RCM instantaneous runoff in the first column for ease of comparison.”)

Reply: We have revised Figure 3 based on your and Reviewer 2's comments (p. 24). See our reply to your comment 10.

Figure 7 shows the average two-day cycle of moulin discharge (Q) for IDC1 during July 2015 derived from Figure 3. As such, Figure 7 is "a zoom on some relevant period" as the reviewer suggested. We have better illustrated Figure 7 to compare different routing models: "A magnified example of this timing is seen in Figure 7, which presents the average two-day cycle of moulin discharge input using the three routing models overlaid with effective pressure in IDC1. All three routing models achieve minimum moulin discharges around 09:00-11:00 and minimum effective pressures around 17:00-19:00, yielding a time lag of 8-9 hours; in contrast, the RCM instantaneous runoff without routing achieves minimum moulin discharge around 00:00 and minimum effective pressure around 10:00. The timing of effective pressure produced using RCM instantaneous runoff is visibly different than with the routing methods; interestingly, the timing of minimum effective pressure simulated by the RCM instantaneous runoff is very close (~ 1 hour) to that of maximum effective pressure simulated by the routing models", as requested (p. 27).

39. ("Figure 4: Figure four is barely described in the text, it should either be better described or completely omitted.")

Reply: Figure 4 shows scatter plots of RWF-routed moulin diurnal discharge range (difference between maximum and minimum moulin discharge) vs. those modeled from RCM instantaneous runoff, SUH routing, and SRLF routing. We now think it is not closely related with the main topic of this study so we have deleted it, as suggested.

40. ("Figure 5: Ac is given here in km2, it should be given in m2 for consistency with the rest of the manuscript. The caption here could be shortened to its descriptive part.")

Reply: The area unit has been changed into "m^2" and the caption has been shortened, as requested (Figure S5).

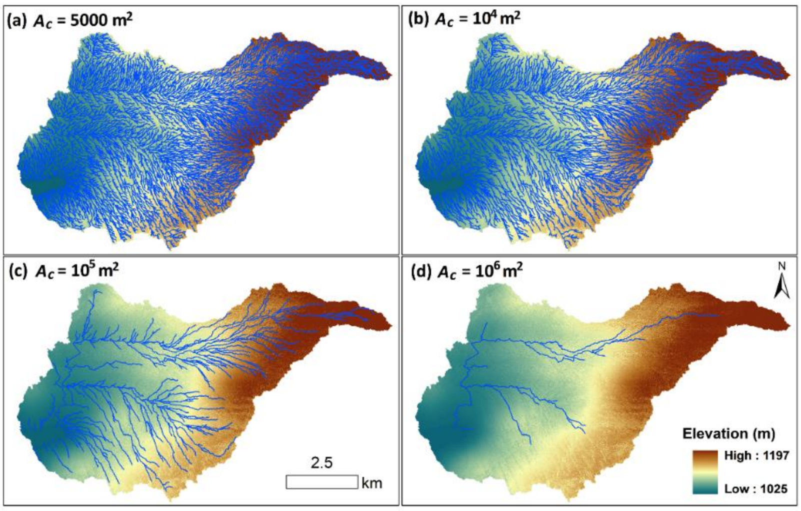

Figure S5. Variable supraglacial stream/river network for IDC1, as simulated by applying variable accumulative area threshold (Ac) values to ArcticDEM.

41. (“Figure 7: As for Figure 3 this figure is quite busy and should be simplified. The caption here is not adequate with some description missing and some discussion points that could be stripped.”)

Reply: Figure 7 has been simplified and better explained, as requested (p. 27). See our reply to your comment 10.

42. (“References: dois are missing from the references”)

Reply: DOIs have been added, as requested (p. 19-22).

References

Banwell, A., Hewitt, I., Willis, I., & Arnold, N. (2016). Moulin density controls drainage development beneath the greenland ice sheet. Journal of Geophysical Research: Earth Surface, 121 (12), 22482269. doi: 10.1002/2015JF003801

Bartholomew, I. D., Nienow, P., Sole, A., Mair, D., Cowton, T., King, M. A., & Palmer, S. (2011). Seasonal variations in greenland ice sheet motion: Inland extent and behaviour at higher elevations Earth Planet. Sci. Lett., 307 (3-4), 271-278. doi: 10.1016/j.epsl.2011.04.014

Chandler, D. M., Wadham, J. L., Lis, G. P., Cowton, T., Sole, A., Bartholomew, I., . . . Hubbard, A. (2013). Evolution of the subglacial drainage system beneath the Greenland Ice Sheet revealed by tracers Nat. Geosci., 6 (3), 195-198. doi: 10.1038/ngeo1737

de Fleurian, B., Morlighem, M., Seroussi, H., Rignot, E., van den Broeke, M. R., Munneke, P. K., . . . Tedstone, A. J. (2016). A modeling study of the eect of runovariability on the eective pressure beneath Russell Glacier, West Greenland. J. Geophys. Res, 121 (10). doi: 10.1002/2016JF003842

Flowers, G. E. (2018). Hydrology and the future of the greenland ice sheet. Nat. Comm., 9 (2729). doi: 10.1038/s41467-018-05002-0

Smith, L. C., Yang, K., Pitcher, L. H., Overstreet, B. T., Chu, V. W., Rennermalm, Å. K., . . . Behar, A. E. (2017). Direct measurements of meltwater runoff on the Greenland ice sheet surface. Proceedings of the National Academy of Sciences, 114 (50), E10622E10631. doi: 10.1073/pnas.1707743114

Reviewer #2:

General Comments: There has been a significant amount of recent work done on capturing processes influencing moulin hydrographs on sub-diurnal timescales. Going forward with these approaches will require significant investment of resources, particularly if field-derived empirical parameters are needed to calibrate supraglacial hydrology models. Underlying this work is an assumption that moulin discharge variability at sub-diurnal timescales might impact the evolution of inter- and sub-glacial hydrological networks, and thus ice dynamics. If this is the case, then supraglacial hydrological processes necessitate further investment to be properly constrained at fine temporal and spatial scales. However, the impact of supraglacial discharge variability on subglacial hydrology has not yet been investigated, and it is therefore not clear if, where, and what specific investments are needed. In this context, this paper makes two major contributions:

1) This paper is a first attempt to investigate the extent to which moulin hydrographs matter for subglacial channel evolution and effective pressure on diurnal timescales.

2) This paper evaluates three different contemporary approaches to estimating daily moulin hydrographs and evaluates the consequences of each with respect to modelled evolution of subglacial channel evolution and effective pressure.

This paper therefore constitutes an original and valuable contribution to ongoing research on supraglacial hydrology.

1. ("The paper could be improved by clarity and specificity around the methods used and the objectives of the paper. Suggestions in this respect are provided below and in the accompanying annotated PDF. My comments focus primarily on the supraglacial hydrology components of the study.")

Reply: We have better clarified the methods and the objective of the paper, as requested. We agree with the reviewer that the methods should "be made clearer for a glaciology (rather than a hydrology) readership" since the objective of the paper is to illustrate the impact of surface meltwater routing on subglacial effective pressure rather than to directly compare the three surface meltwater routing methods. We have carefully revised the supraglacial hydrology components of the study, as requested (p. 4, lines 2-15; p. 5, lines 13-31; p. 6, lines 1-16; p. 7, lines 1-13; p. 8, lines 2-8). We have also included Table S1, which simply explains the benefits of using different routing models.

2. ("Specific comments: Title: Only one of the models is a routing model. Consider saying 'inter-comparison of moulin hydrograph estimations' or something similar. Throughout: The use of 'routing models' seems inaccurate. Only one (the SRLF) approach is a flow routing approach. The other two (RWF and SUH) do not route flow. A different word choice would be preferable. A 'comparison of hourly moulin discharge models', or something similar…..")

Reply: We suggest that the three models (SUH, RWF, and SRLF) are all routing models. A routing model does not need to explicitly determine how meltwater produced on a cell is routed to its downstream cell(s) in a catchment, which is the aim of spatially-distributed routing models. In contrast, a routing model can be lumped and only determines how surface meltwater produced in the catchment is temporally routed to the catchment outlet. Unit hydrograph (UH) is designed for this purpose. UH is a transfer function that models catchment runoff response to rainfall (melt in our case) events for some unit duration and unit depth of effective water input. In this study, all the three models (SUH, RWF, and SRLF) exhibit their UHs and consequently can temporally route surface meltwater to the catchment outlet and yield moulin discharge hydrographs. From this perspective, we suggest that they are all routing models. This point has better explained (p. 5, lines 20-23).

Moreover, RWF and SRLF actually work very similarly. SRLF uses Manning's open-channel equation to calculate meltwater flow velocity for each cell of a catchment, while RWF uses constant hillslope and open-channel flow velocities calibrated from field measurements to determine each cell's flow velocity. As such, RWF and SRLF both generate a velocity raster. Then, integrating velocity with flow path distance calculated from DEM, meltwater transport time from each cell to the catchment outlet can be determined and the transport time distribution yields UH. In short, the primary difference between RWF and SRLF is the way they determine flow velocity for each cell.

We have added Table S1 to summarize the benefits of using different routing models and better illustrated the three routing models in the methods and data section (p. 4, lines 2-15; p. 5, lines 13-31; p. 6, lines 1-16; p. 7, lines 1-13; p. 8, lines 2-8).

Table S1. A brief summarization of surface meltwater routing models.

Model	Meltwater Routing	Applicable on bare ice surfaces		Applicable on snow surfaces	Parameter dependency	DEM dependency	Case study
		Hillslope	Open-Channel				
Instantaneous RCM runoff	No	-	-	Yes	No	No	(McGrath et al., 2011; Bartholomew et al., 2012; Rennermalm et al., 2013; Fitzpatrick et al., 2014)
Snyder Synthetic Unit Hydrograph (SUH)	Yes	-	-	Yes, but model parameters should be recalibrated	C_p, C_t are calibrated using a field-measured moulin hydrograph	No	(Smith et al., 2017)
Surface Routing and Lake Filling (SRLF)	Yes	No	Yes	Yes	No	DEM is required to calculate meltwater flow velocities for all catchment cells	(Arnold et al., 1998; Willis et al., 2002; Banwell et al., 2012; Banwell et al., 2013; Arnold et al., 2014; Banwell et al., 2016; de Fleurian et al., 2016; Koziol and Arnold, 2018)
Rescaled Width Function (RWF)	Yes	Yes	Yes	Yes, but model parameters should be recalibrated	Hillslope and open-channel flow velocities (v_h and v_c) are calibrated using a field-measured moulin hydrograph	High-resolution (<10 m) DEM is required to calculate hillslope flow path length	(Yang et al., 2018)

3. (“Introduction: In general, I do not find that the introduction sets up the objectives of the paper very well. It does not provide sufficient information to set up a methods comparison, but also only emphasizes the subglacial channel evolution at the end – like an afterthought. I suggest the following changes: - You need to be clearer in your introduction that this is not a methodological paper per se – as you say later in the paper, you cannot say which method performs better due to a lack of empirical evidence. You can only speculate on the modelled (not observed) hydrological implications of the three different methods. This needs to come across more strongly.”)

Reply: We have included the following statement in the Introduction: “Notably, this study cannot, in good faith, focus on method comparison, nor determine the ‘best’ (i.e., best able to reproduce a real-world moulin hydrograph) due to the lack of calibration and validation data. Owing to this limitation, the goal of this study is to assess differences among the three meltwater routing models, rather than revealing which model most realistically simulates surface meltwater routing on the ice surface. By using the outputs from all three as meltwater inputs to drive the SHAKTI subglacial model, we characterize the impact of their differences on subglacial effective pressure, and, more generally, the importance of routing supraglacial runoff on subglacial conditions”, as requested (p. 4, lines 6-15).

4. (“The differences between the three approaches as well as the assumptions and limitations of each needs to be made clearer for a glaciology (rather than a hydrology) readership. The limitations of the empirically-derived RWF and SUH also need to be made clear, particularly the temporal limitations of the original field-derived moulin hydrograph measurement. As is, a comparison of these three approaches is only useful for conditions similar to those under which the SUH and RWF approaches are calibrated – this needs to be made clear.”)

Reply: We have better explained the three approaches and made them clearer for the glaciology readership, including the addition of Table S1. The limitations of the empirically-derived RWF and SUH have been made clearer, as requested (p. 14, lines 6-13).

SUH and RWF both rely on several empirically parameters (C_p and C_t for SUH, and v_h and v_c for RWF) calibrated from a moulin hydrograph measured at the Rio Behar catchment, southwest GrIS during a very short time period (72 hours), July 2015 (Smith et al., 2017). In contrast, SRLF is more solid because it only relies on DEM to calculate meltwater flow velocities (Banwell et al., 2012). In this study, we assume these empirically parameters are transferable over space and time but this assumption needs further validation. It may hold for ice sheet surface with similar hydrologic and glaciological environments but it may be problematic to apply over larger space and longer time. A second independent, long-term moulin hydrograph will help to address this problem.

5. (“Because the comparison between the approaches is inherently limited due to the temporally-limited nature of the field moulin discharge measurements in the SUH and RWF, I think it would be useful in the introduction to put more emphasis on the goal of the paper as an exercise in examining (modelled) subglacial effective pressure sensitivity to diurnal

hydrographs, rather than explicitly a comparison of moulin discharge estimate approaches. I would consider a bolder introductory statement around Page 2, Line 17 that frames the paper as a (preliminary) investigation of the extent to which moulin hydrograph estimates matter for affecting modelled subglacial hydrology and effective pressures.")

Reply: We have included two modifications to the introduction to emphasize the importance of the supraglacial system on subglacial hydrology. First, the current lack of representation of the surface meltwater routing leads to an insufficient understanding of surface-to-bed meltwater connections and ice dynamics, particularly on diurnal timescales. Therefore, constraints on IDC discharge can provide critical boundary conditions for studies of the subglacial hydrologic system (p. 2, lines 28-30). Second, by using the outputs from all three as meltwater inputs to drive the SHAKTI subglacial model, we have characterized the impact of their differences on subglacial effective pressure, and, more generally, the importance of routing supraglacial runoff on subglacial conditions (p. 4, lines 2-5). We have also emphasized the subglacial results in the last line of the abstract (p. 2, lines 3-6). We thoroughly discuss the implications of these different surface meltwater routing models on subglacial hydrology in section 4.2.

6. ("Last paragraph of introduction. I think there needs to be more explanation of what you are hoping to achieve with using the SHAKTI model. I think you need to be explicit that there is no objective away to compare the three moulin hydrograph methods, and the differences between them only matter in a glaciological sense if they significantly impact subglacial hydrology and effective pressure. You therefore run what is loosely a sensitivity test using SHAKTI to assess the modelled impacts of each approach. Although this comes out later in the paper, you need more framing of this consideration in the introduction.")

Reply: See our reply to your comment 3. We have revised the last paragraph of introduction to better illustrate the objective of this study and explicitly indicate our goals with the lines: "By using the outputs from all three routing models as meltwater inputs to drive the SHAKTI subglacial model, we seek to characterize the impact of differences in surface routing on subglacial pressures and evolution, particularly over diurnal timescales. More generally, these results can demonstrate the extent to which the choice of surface meltwater routing algorithms can alter modelled subglacial conditions", as requested (p. 4, lines 6-15).

7. ("Study area and datasets: More specific justification of the chosen study IDCs is needed. They are approximately similar sizes to the IDC used in the Smith et al. (2017) measured moulin hydrographs, which should be pointed out, and they also appear to exclude large supraglacial lakes, which is likely to affect the comparison of the SRLF approach with the RWF and SUH approach. This should be noted in the study area description and in the discussion.")

Reply: We have better explained the reasons to select the four IDCs: "They are distributed at approximately 200 m elevation intervals in order to span the elevational range of most well-developed IDCs found in the Russell Glacier region and the variable surface melt conditions of this region (Yang and Smith, 2016). Large supraglacial lakes are absent in these four IDCs

(Figure 1) and surface meltwater is all routed to the moulin at the catchment outlet. As such, surface runoff produced in each IDC equals to the moulin discharge (Smith et al., 2017). A moulin discharge hydrograph collected at Rio Behar catchment (IDC2 in this study; 67.049346N, 49.025809W) for 72 h from 20 to 23 July 2015 was used to calibrate parameters of SUH and RWF models (see Sections 2.5 and 2.6). It is problematic to apply these empirically-derived parameters over large spaces and long times (Yang et al., 2018). Therefore, the selected IDCs are distributed in a relatively small region and the areas of IDC1, IDC3, and IDC4 are similar to the Rio Behar catchment (IDC2)", as requested (p. 4, lines 20-31).

We have better illustrated the limitations of SUH and RWF in the discussion section, as requested: "SUH and RWF both rely on several empirically parameters (C_p and C_t for SUH, and v_h and v_c for RWF) calibrated from a moulin hydrograph measured at the Rio Behar catchment, southwest GrIS during a very short time period (72 hours), July 2015 (Smith et al., 2017). In contrast, SRLF is more solid and applicable over large spaces and long times because it only relies on DEM to calculate meltwater flow velocities (Banwell et al., 2012). In this study, we assume these empirically parameters are transferable over space and time but this assumption needs further validation. It may hold for ice sheet surface with similar hydrologic and glaciological environments but is problematic to apply over larger space and longer time. A second independent, long-term moulin hydrograph will help to address this problem" (p. 14, lines 6-13).

8. ("Methods: Overall, the methods seem written for hydrologists, not for glaciologists. More information is needed in this section to make it useful to its readers.")

Reply: We have better introduced the three routing models from a perspective of glaciologists. A new section has been added to explain Unit Hydrograph and its application for calculating moulin discharge. Additional new text has been added to better explain Snyder Synthetic Unit Hydrograph, Surface Routing and Lake Filling, and Rescaled Width Function, as requested (p. 4, lines 2-15; p. 5, lines 13-31; p. 6, lines 1-16; p. 7, lines 1-13; p. 8, lines 2-8).

9. ("Presumably, July 2015 was chosen for the MAR runoff simulations because that is coincident with the field-collection of the moulin discharge hydrograph. This should be made clear, so that the constraints on the method are obvious to readers.")

Reply: Yes, July 2015 runoffs were derived to be coincident with the field-collection of the moulin discharge hydrograph. Additional new text has been added to explain this point, as requested (p. 5, lines 8-9).

10. ("If this paper is to be a useful methodological resource for glacier hydrologists, a more complete comparison of the three approaches is needed. Perhaps a table would be useful in comparing the three methods – this table could keep track of the references, acronyms, assumptions, limitations, etc…")

Reply: Thanks for this great comment. We have added a new table (Table S1) to better compare the three routing models, as suggested (see our reply to your comment 2).

11. ("Section 3.6 – your explanation of a 'dynamic' Ac is not clear, or perhaps I have missed it. In Figure 3, it looks like you tested all five of the different Ac values independently over the whole time span, but then there is also a 'dynamic Ac'. Is a 'dynamic' Ac one that evolves according to your six five-day RWF-UHs? Be sure to call that 'dynamic' here.")

Reply: Yes, we tested all five of the different A_c values independently over the whole time span and then a 'dynamic' A_c one evolves according to the six five-day RWF-UHs, as the reviewer pointed out. We have added a new sentence "Each RWF UH was conducted to calculate moulin discharge for five days and the resultant moulin discharge is termed as dynamic A_c discharge" to better explain dynamic A_c, as requested (p. 8, lines 20-21).

12. ("Results: the figures for this section are confusing. They need to be pulled apart to be more readable, and the legends and captions need better information.")

Reply: We have carefully revised the figures to make them more readable, as requested. See our reply to your following comments (p. 24-28).

13. ("Figure 3 is too confusing with this many panels, and the result is that the lines are too small to make out the subtle differences due to the different variables. I suggest taking the third column (effective pressure) out and putting it in its own figure, as it is a distinct part of the results and discussion. You could then make the main figure slightly larger, and show with a title on the legend in (g) and (j) that the different series refer to g) the DEM resolution and j) the channel initiation threshold (proxy for time).")

Reply: We have taken the third column (effective pressure) and put it in its own figure, as the reviewer suggested (Figures S1 and S2). We have made Figure 3 larger and reshaped the width ratio between the first column (UH) and the second column (moulin discharge) from 1:1 to 1:1.5 to better represent the diurnal moulin discharge. We have added a title "DEM resolution" to Figure 3c and 3e, and a title "Ac" to Figure 3g, changed the x-axis labels of Figure 3e and 3g into "RWF UH (A_c = 100 m^2) and "RWF UH (2 m DEM), respectively, and added legend "RCM runoff" to Figure 3b, 3d, and 3f. We have better explained "the channel initiation threshold (proxy for time)" in the caption of Figure 3.

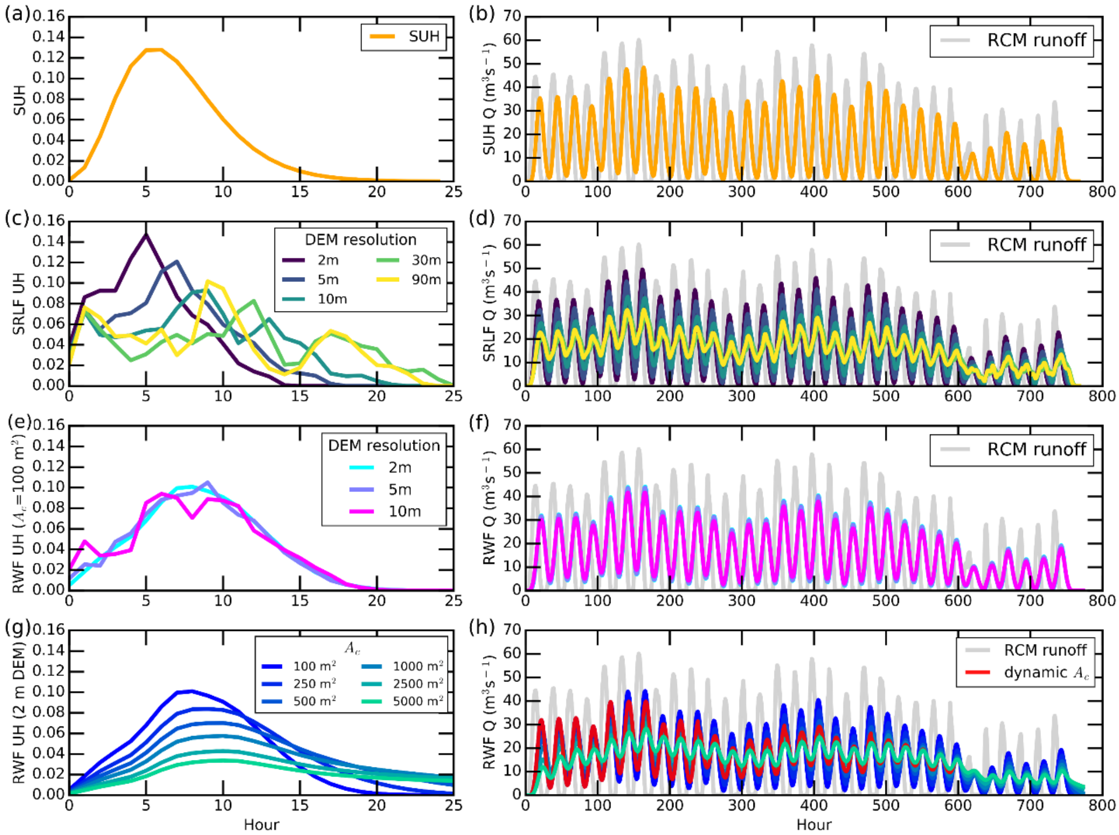

Figure S1. Presentation of Unit Hydrographs (UHs) (column 1) and moulin discharges (column 2) of IDC1 during July 2015, as simulated by three supraglacial routing models (SUH, SRLF, and RWF). A_c is the cumulative contributing area required to initiate a supraglacial meltwater channel and dynamic A_c values are used as proxy for time to simulate the temporal evolution of supraglacial stream/river networks. Simultaneous RCM runoff (grey line) is shown to indicate the effect of surface meltwater routing process on moulin discharge.

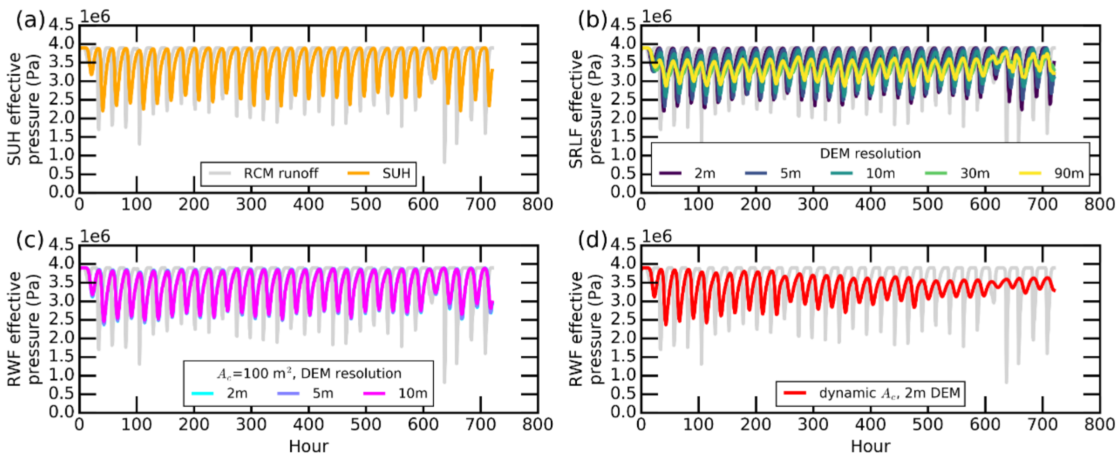

Figure S2. Effective pressures for IDC1 simulated by SHAKTI, with inputs to the subglacial system via a single moulin prescribed by the moulin discharges (shown in Figure S1) calculated by the various routing models. The effective pressure shown here is the spatial mean for the entire 1-km square domain which contains the moulin input at its center.

14. ("Figure 4 is not discussed in the results section. Some discussion should be provided in the 'long-term evolution' section, or it should be removed.")

Reply: We agree Figure 4 is not closely related with the main topic of this study so we have removed it, as suggested.

15. ("Figure 3k – how is that there is so much smaller discharge for 5000m^2 than there is for 100m^2? With a higher Ac, there should be less efficient routing, lower peak Q and a flatter hydrograph but still, presumably, similar discharge. This distinction is not clear from the figure, perhaps because the lines are so compressed and the 'flashiness' of the hydrographs is not clear. Perhaps an inset figure would be helpful.")

Reply: A_c = 5000 m^2, as the reviewer pointed out, yields lower peak Q and a flatter hydrograph than A_c = 100 m^2 but it also yields higher minimum Q. Therefore, the daily Q values calculated from A_c = 5000 m^2 and A_c = 100 m^2 are similar.

16. ("Discussion: Overall, I think this section is too critical of SRLF and not critical enough of SUH and RWF. Some discussion of the limitations of the latter two is needed, namely: the chosen study catchments do not appear to have lakes, and those methods may not perform adequately in catchments with lakes, at different times of year and in different snow/ice/ surface slope conditions than those in which the field-measurements of the moulin hydrograph (Smith 2017) were collected.")

Reply: SRLF is the first model to route surface meltwater on the Greenland Ice Sheet. We think it is very successful. The SRLF model employs Darcy's law to route surface meltwater flow through snow and Manning's open-channel flow equation to route meltwater flow over bare-ice surfaces (Arnold et al., 1998). SRLF has been applied to simulate supraglacial lake growth and to drive subglacial hydrological evolution during several entire melt seasons (Banwell et al., 2012; Banwell et al., 2013; Arnold et al., 2014; Banwell et al., 2016). In this study, we focus on its bare-ice part to make it comparable with the SUH and RWF because the coefficients of these two models were calibrated using a field-measured moulin hydrograph on bare ice surface (Smith et al., 2017; Yang et al., 2018). It may 'hurt' the full ability of SRLF model as the reviewer pointed out.

To address this problem, we have: (1) better introduced SRLF model in the methods and data section (p. 6, lines 8-16), and (2) better discussed the limitations of SUH and RWF as requested (p. 6, lines 3-6; p. 7, lines 9-12; p. 14, lines 6-13). We have illustrated the limitations of SUH and RWF in detail in our previous studies (Smith et al., 2017; Yang et al., 2017) so we have only illustrated their limitations when comparing with SRLF and driving subglacial hydrology.

17. ("More discussion of the limitations of SHAKTI would be helpful. You should be clear that SHAKTI is used to provide preliminary insight into the possible importance of accurately capturing the details of an hourly moulin hydrograph, and that many complexities are not

captured by this model.”)

Reply: The limitations of SHAKTI itself are enumerated in Sommers et al. (2018). We have included a statement indicating the limitations of the model runs themselves in the results section: “The subglacial model domain and duration were chosen to illustrate the impact of the chosen supraglacial routing model on local subglacial hydrology in the vicinity of a moulin input at the bed. As such, our results cannot necessarily be extrapolated to infer large-scale or seasonal evolution of the subglacial hydrologic system in response to different surface forcings; however, the results do provide insight into the potential diurnal sensitivity of the subglacial system to changes in supraglacial meltwater routing and the associated modification of the discharge hydrograph” (p. 11, lines 20-32).

In the updated manuscript, we have rerun the SHAKTI simulations with more realistic boundary conditions, surface slopes, and sliding velocities for each catchment to better represent actual effective pressures that may be found in the vicinity of a moulin in each region. The reviewer is correct that this is a simple exploration of the influence of different surface meltwater methods on subglacial pressures, but we hope that it provides a view into these connections and may serve as inspiration and motivation for more detailed studies involving simulations of multiple catchments with multiple realistic moulin inputs, topography, etc. In terms of capturing complexities of the subglacial drainage system, even with these small-scale simulations, the SHAKTI model does realistically represent realistic flow and pressure regimes, and evolving geometry under the ice in the vicinity of a moulin.

Technical corrections: Please see specific in-text comments in the attached annotated PDF. Please also note the supplement to this comment:

18. (“P2, line 12, Flowers, 2018, I would drop this reference as you provide specific references in the next sentence.”)

Reply: This reference has been deleted, as requested (p. 2, line 18).

19. (“P2, line 31, “field-measured moulin hydrograph”, more information needed. Be clear that this is based on one moulin for one moment in time - make the limitations clear.)

Reply: The field-measured moulin hydrograph was collected at Rio Behar catchment, southwestern GrIS (67.049346N, 49.025809W) for 72 h from 20 to 23 July 2015. Although Smith et al. (2017) demonstrated coefficient transferability using two other independently field-measured moulin hydrographs, the two calibrated coefficients are collected at “one moulin for one moment in time” as the reviewer pointed out so they may still be limited to apply over longer time and larger areas. Additionally new text have been added to explain this point, as requested (p. 4, lines 27 -31).

20. (“P3, lines 3-4, “Catchment-averaged meltwater transport velocities for each zone were then calibrated using a field-measured moulin hydrograph (Smith et al., 2017)”, More information needed. Be clear that this is based on one moulin for one moment in time - make the limitations clear.)

Reply: See our reply to your comment 19.

21. ("P3, line 6, "it only requires catchment shape and area to estimate surface meltwater transport time (Smith et al., 2017)", As well as a number of important empirically-derived parameters. That should be made clear here.")

Reply: Changed as requested (p. 3, line 23).

22. ("P4, line 5, "RCM runoff simulations", Avoid acronyms in the subtitles.")

Reply: This subtitle has been changed into "2.2 Regional climate model runoff simulations", as requested (p. 5, line 8).

23. ("P4, line 14, "field-measured moulin hydrograph", Specify where and when this data was collected.)

Reply: This data was collected at Rio Behar catchment, southwestern Greenland Ice Sheet (67.049346N, 49.025809W) for 72 h from 20 to 23 July 2015. Additional new text has been added to explain this point (p. 5, line 30).

24. ("P4, line 23, If you are going to supply the equation here, supply it for the relevant SUH equations above as well.)

Reply: The relevant SUH equations have been added, as requested (p. 5, lines 26-29).

25. ("P4, line 28, Spell this out here - it is difficult to keep track of all the acronyms.)

Reply: Changed as requested (p. 6, lines 24-25).

26. ("P5, lines 14-19, Make this its own section - at the moment, it is tucked under RWF. Alternatively, move it to the introduction or to section 3.7")

Reply: We have removed this paragraph to the introduction section, as suggested (p. 4, lines 6-15).

27. ("P6, lines 1-2, Is it possible that the empirical parameters Cp and Ct might change seasonally?)

Reply: Good point. C_p and C_t are two empirical parameters that quantify the hydrologic response of a catchment to surface melt. If we can have a moulin discharge hydrograph during the entire melt season, we can calculate multi-temporal C_p and C_t using variable time-to-peak (t_p), peak discharge (h_p), and main-stem stream length (L), thus creating multi-temporal SUHs. Without such direct measurements, the parameters cannot be realistically varied in time and SUH cannot mimic variable hydrologic response of a catchment to surface melt. We have better explained this point in the Methods and Data section (p. 8, lines 5-8).

28. (“P7, line 8, I keep getting up on routing. These are not routing processes in the RWF and the SUH??”)

Reply: See our reply to your comment 2.

29. (“P7, line 14, But of course this is the catchment from which the empirical parameters are derived, so is the comparison really appropriate? At least make it clear.”)

Reply: We agree with the reviewer that this comparison is limited since we do not have a second field-measured moulin discharge hydrograph as validation data. But we suggest that this comparison at least indicates the transferability of these empirical parameters (C_p and C_t for SUH, and v_c and v_h for RWF) from the field-measured catchment to other catchments with similar areas. The limitation of the comparison has been better explained, as requested (p. 9, line 29; p. 14, lines 6-13).

30. (“P7, line 28, Is this really 'long term'? 'Temporal evolution' would be better.”)

Reply: We have changed ‘long-term’ into ‘temporal’, as suggested (p. 12, line 1).

31. (“P11, line 17, Should be decreases because subglacial water pressure will increase?”)

Reply: Good catch! Changed and clarified to: effective pressure decreases, resulting in increased sliding velocities (p. 14, line 21).

32. (“P21, Figure 3, Remove the 'UH' - it looks as though you are subtracting a function from a function. With this legend down here, it is not clear that the grey refers to all plots. Is only 100 and 5000m2 showed in this figure? If so, it should say so in the legend.)

Reply: ‘UH’ has been removed, as requested. The grey refers to all plots and moulin discharge hydrographs for all six cumulative area thresholds are showed in Figure 3k. We have revised Figure 3 to make it more understandable (p. 24-25).

33. (“P22, Figure 4, This figure is not explained in text and its context is therefore not clear”)

Reply: We now think Figure 4 is not closely related with the main topic of this study so we have removed it, as suggested.

34. (“P25, Figure 7, Why are there two solid lines and two dashed lines in each? What do the grey lines mean? Are they RCM discharges?”)

Reply: Two solid lines are supraglacial moulin discharge and two dashed lines are effective pressure. The grey solid lines are RCM surface runoff and the grey dashed lines are effective pressure simulated from RCM surface runoff. All the line colors correspond with the ones in Figure 3. This point has been better explained. We have updated Figure 7 to make it more understandable (Figure S3).

The average two-day cycle is presented because the average one-day cycle cannot present complete results for all models. All the three routing models achieve minimum moulin discharges around 09:00-11:00 and minimum effective pressures around 17:00-19:00, yielding a time lag of 8-9 hours; in contrast, the RCM instantaneous runoff without routing achieves minimum moulin discharge around 00:00 and minimum effective pressure around 10:00 (Figure S3). All three routing models achieve minimum moulin discharges around 09:00-11:00 and minimum effective pressures around 17:00-19:00, yielding a time lag of 8-9 hours; in contrast, the RCM instantaneous runoff without routing achieves minimum moulin discharge around 00:00 and minimum effective pressure around 10:00. The timing of effective pressure produced using RCM instantaneous runoff is visibly different than with the routing methods; interestingly, the timing of minimum effective pressure simulated by the RCM instantaneous runoff is very close (~ 1 hour) to that of maximum effective pressure simulated by the routing models.

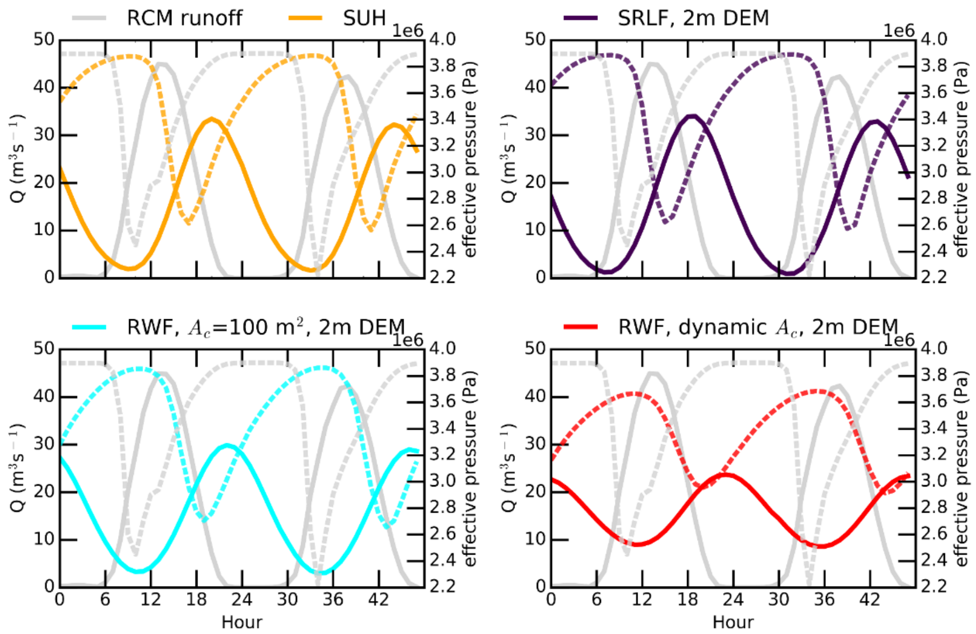

Figure S3. The average two-day cycle of moulin discharge (Q) for IDC1 during July 2015. The daily minimum input in supraglacial moulin discharge (solid lines) corresponds generally to maximum effective pressure (dashed lines), and is followed within 8-9 hours by the daily minimum effective pressure (maximum subglacial water pressure). This suggests that the system shuts down due to creep with low meltwater input, and becomes highly pressurized as meltwater input increases again. As the new water inputs are accommodated, efficient pathways reform and effective pressure increases (subglacial water pressure decreases).

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Thank you for considering this manuscript for publication in ***The Cryosphere***. If we may provide any additional information about the dataset or analysis, please do not hesitate to contact us at yangkangnju@gmail.com.

Respectfully submitted,

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Inter-comparison of surface meltwater routing models for the Greenland Ice Sheet and influence on subglacial effective pressures

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Abstract. Each summer, large volumes of surface meltwater flow over the Greenland Ice Sheet ~~(GrIS)~~ surface and drain through moulins to the ice sheet bed, and impact~~ing~~ subglacial hydrology and ice flow dynamics. Runoff modulations, or routing delays due to ice sheet surface conditions, ~~thus~~ propagate to englacial and subglacial hydrologic systems and ~~requiring~~ require accurate assessment to correctly estimate subglacial effective pressures and short-term lags between surface meltwater~~climatological melt~~ production and ice ~~velocity~~motion. This study compares hourly supraglacial moulin discharge simulations from three surface meltwater routing models, (1) synthetic unit hydrograph, (2) surface routing and lake filling, and (3) rescaled width function, for four internally drained catchments ~~(IDCs)~~ located on the southwestern ~~GrIS~~ Greenland ice sheet surface. Using surface runoff from the Modèle Atmosphérique Régionale~~MAR~~ regional climate model (RCM), simulated variables used for~~values of~~ surface meltwater routing ~~transport velocity, flow length, total transport time, unit hydrograph, peak moulin discharge, and time to peak~~ are compared among the three routing models. For each catchment~~IDC~~, ~~modeled~~ simulated moulin hydrographs are used as input to the SHAKTI subglacial hydrologic model to ~~simulate~~ produce corresponding subglacial effective pressure variations in the vicinity of a single moulin. Two routing models, surface routing and lake filling and rescaled width function, ~~requiring~~ which require the use of a digital elevation model (DEM), ~~(SRLF, RWF)~~ are assessed for the impact of DEM spatial resolution on simulated moulin hydrographs. Surface routing and lake filling is sensitive to DEM spatial resolution, whereas rescaled width function is not. Our results ~~Results~~ indicate ~~SUH, SRLF, and RWF~~the three surface meltwater routing models perform differently in simulating moulin peak discharge and time to peak, with rescaled width function~~RWF~~ simulating ~~slower~~later, smaller peak moulin discharges than synthetic unit hydrograph~~SUH~~ or surface routing and lake filling~~SRLF~~. ~~SRLF routing is sensitive to DEM spatial resolution, whereas RWF is not.~~ We also demonstrate that the ~~Seasonal~~ seasonal evolution of supraglacial stream/river networks ~~is~~ can be readily accommodated by rescaled width function~~RWF~~ but not synthetic unit hydrograph ~~SUH~~ or surface routing and lake filling

models~~SRLF~~. ~~In general~~Overall, all three models produce more realistic supraglacial discharges ~~are superior to~~than simply using RCM runoff outputs without an applied routing scheme; however, ~~but~~ there are significant differences in supraglacial discharge generated by the three models tested~~among them are found~~. This variability among surface meltwater routing models is reflected in SHAKTI subglacial hydrology simulations, which yield~~ing~~ substantially different ~~differing~~ diurnal effective pressure ~~fluctuations~~amplitudes depending on the applied surface meltwater routing model; however, display relatively consistent mean effective pressure across routing models.

1 Introduction

Large volumes of meltwater are routed through supraglacial stream/river networks ~~across the ablation zone of~~on the Greenland ice ~~surface~~ sheet each summer (Smith et al., 2015). In temperate areas of the ice sheet, most of this surface meltwater ~~can be~~is injected to the bed via moulins (Catania et al., 2008;Lampkin and VanderBerg, 2014;Smith et al., 2015;Yang and Smith, 2016;Koziol and Arnold, 2018), where it can modulate ice flow (Bartholomew et al., 2011;Palmer et al., 2011;Banwell et al., 2013;Hewitt, 2013;Andrews et al., 2014;de Fleurian et al., 2016). However, the role of the supraglacial system in controlling subglacial hydrology remains poorly studied to date (Flowers, 2018). In particular, there are limited constraints on the efficiency of surface meltwater routing ~~efficiencies~~ (Smith et al., 2017), resulting in large uncertainties in hydrodynamic coupling with ice motion.

In most studies that investigate surface-to-bed meltwater connections and the behaviour of the subglacial hydrologic system, surface meltwater routing is either simplified or simply ignored, i.e., moulin hydrographs are estimated directly from output of regional climate models (RCMs)~~ (Flowers, 2018)~~. In these instances~~the latter instances~~, RCM instantaneous grid cell runoff is simply summed over ~~a given drainage catchment~~ internally drained catchments (IDCs, "hydrologic units on the GrIS surface that collect and drain meltwater through supraglacial stream/river networks to terminal moulins or lakes") (Yang and Smith, 2016) to estimate supraglacial moulin discharge or to fill supraglacial lakes (McGrath et al., 2011;Fitzpatrick et al., 2014). This summed value is used to drive models of subglacial hydrologic system evolution and/or ice flow dynamics. ~~This~~ Such a simplification may be appropriate for small ~~drainage catchment~~IDCs or for very long-term studies; however, surface meltwater routing has been found to substantially modify ice surface runoff (Banwell et al., 2012;Banwell et al., 2013;Arnold et al., 2014), ~~thus~~ by altering the magnitude and timing of peak moulin discharge (Smith et al., 2017;Yang et al., 2018). As such, surface meltwater ~~supraglacial~~ routing has strong potential to affect subglacial hydrologic system evolution and hydrodynamics, especially for large ~~catchments~~ IDCs and short (i.e., diurnal) time scales. The current lack of representation of the surface meltwater routing leads to an insufficient understanding of surface-to-bed meltwater connections and ice dynamics, particularly on diurnal timescales. Therefore, constraints on IDC discharge can provide critical boundary conditions for studies of the subglacial hydrologic system.

In terrestrial systems, including ice sheet and glacier surfaces, ~~Surface melt~~water routing may be characterized by ~~meltwater~~ transport velocity (v), flow length (L), and transport time (t). Meltwater transport velocity and flow length can be estimated from ice surface topography (Arnold et al., 1998), with the distribution of transport times representing the hydrologic response of a particular supraglacial catchment to surface melt (Yang et al., 2018). Alternately, empirical unit hydrograph (UH, “a transfer function that is widely used for modelling catchment runoff response to rainfall events for some unit duration and unit depth of effective water input” (Smith et al., 2017)) methods can be used to estimate the hydrologic response based on catchment shape and area alone, enabling derivation of moulin hydrographs through convolution of input RCM surface runoff with remotely-sensed UH parameters.

In order to route supraglacial meltwater on ice surfaces, Arnold et al. (1998) and Banwell et al. (2012) developed ~~The~~ the DEM-based Surface Routing and Lake Filling (SRLF) model ~~was developed to route supraglacial meltwater on ice surfaces~~ (Arnold et al., 1998;Banwell et al., 2012). SRLF assumes all meltwater is transported downslope, with Manning’s open-channel flow equation used to calculate spatially variable meltwater transport velocities for every bare-ice DEM pixel.

More recently, the Snyder Synthetic Unit Hydrograph (SUH) (Snyder, 1938) was adapted for use on ice sheets to estimate moulin hydrographs without the need for a DEM (Smith et al., 2017). To do this, Smith et al. (2017) calibrated two key SUH parameters ~~were calibrated~~ using a field-measured moulin hydrograph, and a Gamma function was then used to build individual SUHs for hundreds of remotely-sensed ~~IDCs~~ internally drained catchments (IDCs) (Smith et al., 2017). Because the Snyder SUH is a simple lumped model that does not rely on DEMs, it provides a straightforward ~~(if static)~~but static approach to route surface meltwater to moulins.

Most recently, Yang et al. (2018) utilized Rescaled Width Function (RWF) (D'Odorico and Rigon, 2003) to further partition the bare ice surface into either interfluve (i.e., hillslope) or open-channel zones using high-resolution satellite imagery to discern between the two. Catchment-averaged meltwater transport velocities for each zone were then calibrated using a field-measured moulin hydrograph (Smith et al., 2017), with slow interfluve flow (~10^{-3}-10^{-4} m/s) and fast open-channel flow (~10^{-1} m/s) combined to simulate the downstream moulin hydrograph.

These three surface meltwater routing approaches (SRLF, SUH, and RWF) ~~have~~ use different assumptions and data requirements. SUH is the simplest model; it ~~only~~ requires catchment shape, area, and several empirically-derived parameters to estimate surface meltwater transport time (Smith et al., 2017). In contrast, RWF requires ~~the generally ad hoc~~a partitioning of slow (interfluve) and fast (open channel) flow that can substantially impact the performance of RWF without careful spatial and temporal calibration. Moreover, SRLF and RWF rely on surface DEMs to calculate meltwater flow paths (Yang et al., 2018) and SRLF also relies on DEMs to calculate meltwater routing velocities (Arnold et al., 1998). Characteristics such as slope, flow direction, flow length, drainage area, and drainage networks are readily extracted from DEMs but are scale-dependent (Montgomery and Foufoula-Georgiou, 1993), signifying that DEM spatial resolutions influence their computation (Zhang and Montgomery, 1994;Hancock et al., 2006). This DEM resolution dependence can now be tested with the advance of high-resolution DEM datasets (e.g., 2 m ArcticDEM) of the GrIS surface (Noh and Howat, 2015, 2017, 2018).

To assess supraglacial discharge variability~~these differences~~ among ~~different~~ current surface meltwater routing models, this study simulates surface meltwater runoff through four moderate-size IDCs using the SUH, SRLF, and RWF models described above (Figure 1). ~~Their capabilities in simulations of~~Routing model ability to simulate meltwater transport velocity, flow length, transport time, UH, peak moulin discharge, and time to peak are intra-compared, and the impact of DEM spatial resolution on SRLF and RWF is examined. For all of these models, the consequent effect of using them to drive subglacial effective pressure variations is investigated for the illustrative case of meltwater input to the bed via a single moulin, using the Subglacial Hydrology and Kinetic, Transient Interactions (SHAKTI) subglacial hydrologic model (Sommers et al., 2018). From this, we demonstrate the impact of surface meltwater routing on subglacial effective pressure fluctuations.

Notably, this study cannot, in good faith, focus on method comparison, nor determine the “best” (i.e., best able to reproduce a real-world moulin hydrograph) due to the lack of calibration and validation data. Owing to this limitation, the goal of this study is to assess differences among the three surface meltwater routing models, rather than to determine which model most realistically simulates surface meltwater routing on the ice surface. By using the outputs from all three routing models as meltwater inputs to drive the SHAKTI subglacial model, we seek to characterize the impact of differences in surface routing on subglacial pressures and evolution, particularly over diurnal timescales. Nevertheless, these results demonstrate the extent to which the choice of surface meltwater routing models can alter modelled subglacial conditions. ~~For all of these models, the consequent effect of using them to drive subglacial effective pressure variations is investigated for the simple illustrative case of meltwater input to the bed via a single moulin, using the Subglacial Hydrology and Kinetic, Transient Interactions (SHAKTI) subglacial hydrologic model (Sommers et al., 2018).~~ We conclude with a general discussion of surface meltwater routing on the Greenland ice surface and include some recommendations for best practices and future research.

2 Methods and Data

2.1 Study area and data sources

We selected ~~Four~~ four moderate-size supraglacial IDCs in the Russell Glacier region, southwestern GrIS ~~were selected~~ to explore the impact of SUH, SRLF, and RWF meltwater routing models on moulin discharge and subglacial effective pressure (Figure 1, Table 2). They are distributed at approximately 200 m elevation intervals in order to span the elevational range of most well-developed IDCs found in the Russell Glacier region and the variable surface melt conditions of this region (Fitzpatrick et al., 2014;Yang and Smith, 2016). Large supraglacial lakes are absent in these four IDCs and surface meltwater is all routed to the moulin at the catchment outlet (Figure 1). As such, surface runoff produced in each IDC should equal to the moulin discharge (Smith et al., 2017). The four IDC areas range from 53.0 km^2 to 66.9 km^2; surface elevations vary from 1086 m to 1672 m and ice thicknesses from 854 m to 1432 m (Table 2). A moulin discharge hydrograph collected at Rio Behar catchment (IDC2 in this study; 67.049346N, 49.025809W) for 72 h from 20 to 23 July 2015 was used to calibrate parameters of SUH and RWF models (see Sections 2.5 and 2.6). It is problematic to apply these empirically-derived parameters over large spaces and long times (Yang et al., 2018). Therefore, the selected IDCs are distributed in a relatively small region and the areas of IDC1, IDC3, and IDC4 are similar to the Rio Behar catchment (IDC2).

The high-resolution (2 m) ArcticDEM is the primary data source for our study of surface meltwater routing in the four supraglacial IDCs. ArcticDEM products are created from high-resolution (0.5 m) WorldView-1/2/3 stereo images by Polar Geospatial Center (PGC) and provide an unprecedented opportunity to investigate ice surface landscape and hydrologic processes (Noh and Howat, 2015, 2017, 2018). MAR (Modèle Atmosphérique Régionale) 3.6, a regional coupled atmosphere-land climate model with 20 km native horizontal resolution (Fettweis et al., 2013), provides hourly surface runoff simulations.

2.2 Regional climate model runoff simulations

Hourly simulations of surface runoff (R) during July 2015 were obtained from MAR 3.6 (Smith et al., 2017) in order to be to be coincident with the field-collection of the moulin discharge hydrograph. Supraglacial IDC boundaries were derived from ArcticDEM following the method of Karlstrom and Yang (2016). Catchment-averaged hourly ~~runoff~~ R [mm/h] was obtained by clipping MAR grid pixels with the supraglacial IDC boundaries and summing their corresponding runoff values (Smith et al., 2017). Absent any routing, the resulting area-integrated ~~runoff~~ R is termed RCM instantaneous runoff.

2.3 Unit Hydrograph

A surface meltwater routing model does not need to explicitly determine how meltwater produced on a cell is routed to its downstream grid cell(s) in a catchment, which is the aim of spatially-distributed routing models (Singh et al., 2014). In contrast, a routing model can be lumped and only determines how surface meltwater produced in the catchment is temporally routed to the catchment outlet. Unit hydrograph (UH) is designed for this purpose and provides a transfer function between surface runoff R and moulin discharge Q (i.e., direct hydrograph):

$$Q = R * \mathrm{UH} \quad (1)$$

where * is the convolution operator. For each IDC, convolution of UH with hourly R yields a discharge hydrograph at the catchment outlet (i.e., moulin) and thereby determines how surface meltwater produced in the catchment is temporally routed to the catchment outlet. Therefore, the three surface meltwater routing methods (SUH, SRLF, and RWF) based on UH can be considered routing models.

2.4 Snyder Synthetic Unit Hydrograph

Snyder Synthetic Unit Hydrograph (SUH) (Snyder, 1938) assumes catchment morphometry controls the shape of UH and utilizes the catchment main-stem stream length (L, in km), the distance from the catchment outlet (here, the terminal moulin) to the point on the main channel nearest to the catchment centroid (L_{ca}, in km), and two parameters, C_p and C_t, to determine peak discharge (h_p, in hr^{-1}) and time-to-peak ~~in~~ (t_p, in hours) of SUH as $t_p = C_t(LL_{ca})^{0.3}$, $hp = C_p/t_p$. C_p and C_t are two parameters depending on "units and drainage-basin characteristics" (Snyder, 1938). Smith et al. (2017) used a ~~field-measured~~ moulin discharge hydrograph collected at the Rio Behar catchment during 20 to 23 July 2015 to calibrate C_p and C_t ~~and demonstrated coefficient transferability using two other independently field-measured moulin hydrographs (McGrath et~~

~~al., 2011;Chandler et al., 2013)~~. Following Smith et al. (2017), we use C_p = 0.72 and C_t = 1.61 to determine h_p and t_p of SUHs and employ a Gamma distribution to determine the catchment-specific SUH for each IDC.

Although Smith et al. (2017) demonstrated parameter transferability using two other independently field-measured moulin hydrographs, the two calibrated parameters, C_p and C_t, are collected at one moulin for one moment in time so parameter transferability over large regions and long timescales may still be limited. However, it is reasonable to apply them for the Russell Glacier region, southwestern GrIS during July 2015.

2.5 Surface Routing and Lake Filling

SRLF has been~~is traditionally~~ used to fill supraglacial lakes within supraglacial catchments ~~at the catchment outlet~~ (Banwell et al., 2012). Here we use the model to route surface meltwater downslope to a moulin and subsequently to the ice sheet bed. The SRLF model employs Darcy's law to route surface meltwater flow through snow and Manning's open-channel flow equation to route meltwater flow over bare-ice surfaces (Arnold et al., 1998). SRLF is the first surface meltwater routing model for the GrIS and has been successfully applied to simulate supraglacial lake growth and to drive subglacial hydrological evolution during several complete melt seasons (Banwell et al., 2012;Banwell et al., 2013;Arnold et al., 2014;Banwell et al., 2016;de Fleurian et al., 2016). In this study, we use its bare-ice component to make it comparable with the SUH and RWF (Smith et al., 2017;Yang et al., 2018) and representative of mid melt season conditions in the ablation zone. SRLF assumes universal presence of supraglacial open-channel flow everywhere on bare ice surface, by applying Manning's open-channel flow equation (Manning, 1891) to calculate channelized meltwater velocity v for every pixel along a DEM-derived flow path:

$$v = {R_H}^{2/3} S^{1/2} / n \quad (2)$$

where R_H is the hydraulic radius of the supraglacial meltwater channel, S is water surface slope calculated from DEM, and n is the Manning roughness parameter (Arnold et al., 1998). Following Arnold et al. (1998), we set R_H = 0.035 m and n = 0.05. We calculated S ~~was calculated~~ per pixel using ArcticDEM. The shortest meltwater flow length (L) was determined from ArcticDEM using the D8 flow routing algorithm following Karlstrom and Yang (2016). Meltwater transport time (t) for each DEM pixel was then determined as $t = L/v$. To compare with synthetic unit hydrograph~~SUH~~ and rescaled width function~~RWF~~, a one-hour unit hydrograph ~~UH~~ was calculated by hourly binning the transport time raster (Yang et al., 2018), with the resultant UH termed SRLF UH.

2.6 Rescaled Width Function

The rescaled width function (RWF) routing model partitions surface meltwater transport pathways into interfluve (i.e., hillslope) and open-channel distances (L_h and L_c), to determine two catchment-averaged meltwater velocities (v_h and v_c) to represent routing efficiency over these regions (D'Odorico and Rigon, 2003). Then, the transport time for each pixel in a catchment may be calculated as:

$$t = t_h + t_c = \frac{L_h}{v_h} + \frac{L_c}{v_c} \quad (2)$$

where t_h is the interfluve travel time and t_c is the channel travel time. Similar to SRLF, the shortest meltwater flow path for interfluve and channel transport distances is determined using a DEM (Karlstrom and Yang, 2016), with the relative coverage determined by the extent of supraglacial streams and rivers (Yang et al., 2018). By applying the constant interfluve velocity v_h to interfluve pixels and channel velocity v_c to open channel pixels, the meltwater transport time from every catchment pixel to the moulin can be determined and a consequent catchment UH generated, hereafter referred to as RWF UH. The primary difference between RWF and SRLF is the way they determine meltwater flow velocity for each catchment cell. For RWF, using the in situ moulin hydrograph of Smith et al. (2017), Yang et al. (2018) determined the velocity combination of v_h = 0.0006 m/s and v_c = 0.4 m/s to be the optimal match to field observations. Although v_h and v_c may change notably during the melt season because of variable surface melt intensity and ice surface topography, it is reasonable to assume that v_h and v_c are persistent during a relatively short time period for similar hydrologic and glaciological environments. Therefore, in this study, the optimal velocity combination obtained in (Yang et al., 2018) is assumed to be transferable and used to create RWF UHs~~RWF UHs~~ for the four IDCs.

~~It is impossible to determine which of the three models compared here is “best” (i.e., best able to reproduce a real-world moulin hydrograph) due to the lack of a second, continuously acquired moulin discharge dataset. Owing to this limitation, the goal of this research is to assess differences among the three meltwater routing models, rather than revealing which model most realistically simulates surface meltwater routing on the ice surface. By using the outputs from all three as meltwater inputs to drive the SHAKTI subglacial model, we characterize the impact of their differences on subglacial effective pressure, and, more generally, the importance of routing supraglacial runoff on subglacial conditions.~~

2.7 Controls of DEM resolution on surface meltwater routing

DEM spatial resolution has important impacts on the hydrologic response of terrestrial catchments to precipitation (Zhang and Montgomery, 1994;Hancock et al., 2006). To estimate the control of DEM spatial resolution on ice surface meltwater routing, 2 m resolution ArcticDEM data were resampled to 5 m, 10 m, 30 m, and 90 m resolutions, similar to Zhang and Montgomery (1994), and the corresponding meltwater flow paths, velocities, transport time, UHs, and moulin hydrographs ~~from~~ for SRLF and RWF subsequently calculated. For SRLF, all five resampled DEMs were used. For RWF, only 2 m, 5 m, and 10 m resolutions were used to prevent DEM resolution from exceeding the typical interfluve transport distance, ~10 m for southwestern GrIS (Yang et al., 2018); otherwise, interfluve transport distance would be overestimated and the resultant hydrograph would be inappropriate (Hancock et al., 2006).

2.8 Temporal evolution of surface meltwater routing

The spatial pattern of supraglacial stream/river networks is known to vary significantly during a melt season (Lampkin and VanderBerg, 2014). This affects the hydrologic response (and UH) of a supraglacial IDC as transport distances change

(Montgomery and Foufoula-Georgiou, 1993;van Meerveld et al., 2019). RWF can mimic this effect by varying the partitioning of interfluve versus open-channel zones (Yang et al., 2018). ~~SUH and SRLF, in contrast, assume a stable response because in practice they typically assume a fixed catchment extent or a static DEM, respectively.~~SRLF, in contrast, assumes the bare ice surface has a stable response to the surface melt and uses static meltwater routing velocities to build the UH. SUH relies on C_p and C_t to build the UH. If a moulin hydrograph is available during the entire melt season, we can calculate time evolving C_p and C_t using variable time-to-peak (t_p), peak discharge (h_p), and main-stem channel length (L), thus creating multi-temporal UHs. Without such direct measurements, the parameters cannot be realistically varied in time and SUH cannot mimic variable hydrologic response of a catchment to surface melt.

Capturing the rapid seasonal evolution of supraglacial stream/river networks is challenging (Lampkin and VanderBerg, 2014;Yang et al., 2017) and remains largely ~~undone~~ unperformed (Flowers, 2018), but a positive relationship exists between surface melt and supraglacial drainage density (Yang et al., 2017). As a simplified simulation, this study uses a series of cumulative contributing area (or channel initial threshold, A_c) values (A_c = 100 m^2, 250 m^2, 500 m^2, 1000 m^2, 2500 m^2, 5000 m^2)~~, which define the surface area needed to initiate open channel flow,~~ to simulate the hypothetical seasonal evolution of supraglacial stream/river networks by evolving the partitioning of interfluve vs. open channels and resultant surface meltwater routing simulations (Yang et al., 2018). A_c defines the surface area needed to initiate open channel flow. Larger A_c values will yield smaller open-channel zones because larger contributing interfluve areas are required to form open channels (King et al., 2016). Smaller values of A_c signify periods of intense surface melt and actively flowing, well-developed supraglacial stream/river networks (Smith et al., 2017), whereas larger values signify poorly developed network characteristics of the late melt season (Yang et al., 2018). A total of six 5-day RWF UHs were created for each A_c value, broadly consistent with a decreasing RCM runoff trend during July 2015. Each RWF UH was conducted to calculate moulin discharge for five days and the resultant moulin discharge is termed as dynamic A_c discharge.

2.9 Subglacial hydrology modelling

A variety of numerical models have been formulated to simulate different aspects of the subglacial drainage system and ~~derive~~ compute subglacial effective pressure (defined as the difference between ice overburden pressure and subglacial water pressure) (Flowers, 2015;de Fleurian et al., 2018). To examine the variations in modelled effective pressure resulting from the different surface meltwater routing models considered in this study, we treat their respective ~~outputs~~ moulin discharges as direct meltwater inputs to the bed via a single moulin, and simulate subsequent evolution of the local subglacial drainage system using the SHAKTI model (Sommers et al., 2018).

SHAKTI is built ~~into~~ within the Ice Sheet System Model ~~framework~~ (Larour et al., 2012). Using finite elements, it applies a single set of equations over the entire model domain, conserving mass, energy, and momentum, with a subglacial water flux formulation allowing for local development of both turbulent and laminar flow regimes, as well as regimes corresponding to the broad transition between laminar and turbulent. SHAKTI calculates transient effective pressure, hydraulic head, subglacial gap height, subglacial water flux, and “degree of channelization” (defined as the ratio of the rate of opening by melt to the rate of opening by sliding over bumps in the bed). Subglacial effective pressure and geometry evolve naturally to produce continuous configurations ranging from sheet-like to channelized drainage. A thorough description of the SHAKTI model equations, methods, and features, including limitations, can be found in Sommers et al. (2018).

To examine the influence of different surface meltwater routing models on local subglacial hydrology ~~in an isolated setting~~, we apply meltwater input at a single moulin at the center of a 1 km square domain. The domain is discretized with an unstructured triangular mesh consisting of 614 elements and a typical element edge length of 50 m. Outflow is to the left edge of the square domain, with a Dirichlet boundary condition setting the subglacial water pressure to 50 % of the ice overburden pressure (a reasonable assumption for our drainage catchments far from the ice sheet margin)~~atmospheric pressure~~, and zero-flux pressure boundaries on the other three sides. For each IDC, the mean surface slope and mean ice thickness are used (Morlighem et al., 2017), with the bed slope set equal to the surface slope to create a uniformly thick tilted slab of ice, and sliding velocity is prescribed as 100% of the annual mean observed surface velocity (Table 3)~~and bed slopes are fixed at 0.02 and their mean ice thickness used~~. ~~The SHAKTI model was run as a stand-alone model for these simulations, with a uniform, constant ice sliding velocity of 10^{-6} m s^{-1} (approximately 31 m a^{-1}). Each transient simulation was initialized with the subglacial water pressure equal to 50 % of the ice overburden pressure.~~ Constants and parameter values used in the simulations are summarized in Table 3.

3 Results

3.1 Simulations of supraglacial moulin discharge

Inclusion of surface meltwater routing clearly modifies the timing of peak moulin discharge relative to RCM runoff obtained from MAR ~~climate model~~, with each of the three routing models performing somewhat differently. When RCM instantaneous runoff alone is used to simulate moulin discharge (i.e., no routing), moulin discharges peak between 13:00-15:00 local time for all the four study IDCs (Table 2). Inclusion of routing processes, however, introduces considerable ~~lags~~ delay between the timing of peak RCM runoff generation ~~in each IDC~~ and its arrival at the moulins, with all routing models displaying peak moulin discharges occurring ~~ranging~~ from 17:00 to 23:00 local time (Table 2, Figures 2 and S1-S4).

SUH-routed hydrographs simulate peak moulin discharge between approximately 19:00 and 21:00, a delay of 6 hours compared to the RCM instantaneous peak discharge, while SRLF-routed delays ~~varies~~ vary from 3 hours to 10 hours and RWF-routed delay varies from 7 hours to 10 hours (Table 2). ~~In general, t~~These delays are ~~much~~ longer than ~2 hours measured for small IDCs near ice margins (Shepherd et al., 2009;McGrath et al., 2011;Bartholomew et al., 2012) but are comparable to ~5-7 hours measured for the~~a~~ ~60 km^2 ~~IDC~~Rio Behar catchment, confirming the control of catchment size on surface meltwater routing delays (Smith et al., 2017).

Surface meltwater routing also controls peak moulin discharge magnitude and diurnal discharge range. This observation is clearly demonstrated when examining the derived unit hydrographs (UHs) for each routing model. The UH isolates the impact of basin characteristics on moulin discharge by providing the basin integrated runoff resulting from one cm of surface melt over one hour. The three UHs (i.e., SUH, SRLF UH, and RWF UH) and their routed moulin discharges for the four IDCs are presented in the supplement (Figures S1-S4); the resultant patterns of moulin hydrographs are similar so we use IDC1 to illustrate our results here. For IDC1, the peak values of RWF UHs are lower than SUHs and 2 m SRLF UHs. Therefore, RWF UHs temporally distribute surface meltwater most smoothly (Figures 2a, 2c, and 2e). The peak RWF UH is ~0.10 (Figure 2e), indicating that ~10 % surface meltwater is routed to the moulin during the peak runoff hour (Singh et al., 2014), while the peak values are ~0.13 for SUH (Figure 2a) and ~0.15 for 2 m SRLF UH (Figure 2c).

~~With s~~Smoother UHs yield~~ing~~ smaller peak moulin discharge magnitudes and diurnal discharge ranges~~, –~~. Therefore, inclusion of surface meltwater routing introduces smaller peak moulin discharge relative to the RCM instantaneous peak discharge (Figures 2b, 2d, and 2f). For IDC1, the peak moulin discharges simulated by the three routing models are >25 % lower than the RCM instantaneous peak moulin discharge, while the diurnal discharge ranges are >27 % lower. Among the three routing models, RWF introduces slightly smoother moulin hydrographs than SUH and 2 m SRLF (Figures 2b, 2d, and 2f), yielding small differences in peak moulin discharge (<7%) and diurnal discharge range (<12%). This finding suggests that all three models are more representative of the observed processes than using RCM instantaneous runoff without routing, but that each model collects and distributes surface meltwater with different efficiency.

3.2 Simulations of subglacial effective pressure

When applied to provide meltwater input to the bed via a single moulin, the SRLF, SUH, and RWF meltwater routing models all introduce differences in diurnal and long-term fluctuations in subglacial effective pressure (ice pressure – water pressure) relative to effective pressure produced using RCM instantaneous runoff. The effective pressures presented are spatial mean effective pressures over the entire 1-km square domain of the bed surrounding the moulin input. The resultant pattern of effective pressure simulation is similar among the four IDCs so we focus on IDC1 to illustrate our results here, with results for the other three IDCs presented in the supplement. For IDC1, the temporal mean of the spatial mean effective pressure ~~over the 31-day period~~ is relatively consistent between routing models, varying by < 4% (ranging from ~~4.69~~3.36 MPa ~~in the SUH model~~ to ~~4.87~~3.48 MPa ~~in the SLRF model with 90 m resolution~~). RCM instantaneous runoff produces a slightly higher temporal mean effective pressure of 3.53 MPa. The amplitude of the fluctuations around the mean, however, differs substantially between different routing models (Figure 2 and Figures S1-S4 in the supplement).

The relative magnitudes of diurnal signals seen in the meltwater inputs are reflected in the subglacial response. The effective pressure amplitude scales relative to the meltwater input amplitude, with the largest amplitude produced by the RCM instantaneous runoff inputs (Figures 3). While all surface meltwater routing models dampen these amplitudes as compared to RCM instantaneous runoff, the models that produce relatively high-amplitude moulin inputs correspond to high-amplitude effective pressure variations~~, notably in the 2 m SLRF method which frequently yields zero effective pressure and a diurnal amplitude of ~ 4.5 MPa (Figure 3f). With 90 m DEM resolution, the diurnal amplitude decreases to <~~

~~1 MPa~~. ~~In the dynamic RWF method, the dampening effect displayed in the moulin inputs carries over into the resulting effective pressure cycles (Figure 3d).~~ In all cases a clear preferential pathway develops from the moulin location ~~at the center~~ to the outflow at the left edge of the domain. This efficient channelized drainage pathway evolves and fluctuates with the inputs through time and is characterized by higher gap height and effective pressure (i.e. lower hydraulic head and water pressure) than the surrounding bed perpendicular to flow~~in the y direction~~ (Figure 4, and supplementary animation).

For all surface meltwater routing models, the daily minimum moulin input generally corresponds to daily maximum effective pressure (i.e. minimum water pressure).~~is followed after a lag of a few hours by the minimum effective pressure (~~, The minimum effective pressure (maximum water pressure) occurs several hours later ~~which corresponds to the maximum water pressure,~~ as moulin inputs increase again into a ~~the~~ subglacial system that has shut ~~shuts~~ down due to ice creep in the absence of high meltwater input required to maintain a larger gap height~~)~~. A~~n~~ magnified example of this timing is ~~readily~~ seen in Figure 5, which presents the average two-day cycle of moulin discharge input using the ~~SUH method~~three routing models overlaid with effective pressure in IDC1. All three routing models achieve minimum moulin discharges around 09:00-11:00 and minimum effective pressures around 17:00-19:00, yielding a time lag of 8-9 hours. In contrast, the RCM instantaneous runoff achieves minimum moulin discharge around 00:00 and minimum effective pressure around 10:00. The timing of effective pressure produced using RCM instantaneous runoff is visibly different than with the routing methods. Interestingly, the timing of minimum effective pressure simulated by the RCM instantaneous runoff is very close (~ 1 hour) to that of maximum effective pressure simulated by the routing models.

In general, we find that while the moulin inputs generated by the different surface routing models produce variations in diurnal ~~variations of different magnitude in~~range of effective pressure, the overall channelization behaviour and temporal mean effective pressure over the 31-day simulations are relatively consistent between models. ~~These results suggest that in a fully coupled ice dynamics/subglacial hydrology model, different routing methods may not produce significantly different cumulative effects in effective pressure for simulation time scales greater than daily.~~ The subglacial model domain and duration were chosen to illustrate the impact of the chosen supraglacial routing model on local subglacial hydrology in the vicinity of a moulin input at the bed. As such, our results cannot necessarily be extrapolated to infer large-scale or seasonal evolution of the subglacial hydrologic system in response to different surface forcings; however, the results do provide insight into the potential diurnal sensitivity of the subglacial system to changes in supraglacial meltwater routing and the associated modification of the discharge hydrograph. For example, the amplitude of diurnal effective pressure variation for a particular day may range from < 0.5 MPa to > 3.0 MPa, depending on the surface method used (Figure 3). While future work should pursue broader-scope simulations to more fully investigate the larger- and longer-scale effects of surface input variations on effective pressure and ice dynamics, our results suggest that in a fully coupled ice dynamics/subglacial hydrology model, different routing methods may not produce significantly different cumulative or time-averaged effects in effective pressure for simulation time scales longer than daily.

3.3 ~~Long-term~~Temporal evolution of moulin discharge simulations

~~Long-term evolution of supraglacial stream/river networks is found to substantially alter surface meltwater routing processes and to yield highly dynamic UHs and moulin discharges (Figures 3k, 3i, and 4). This result is consistent with Montgomery and Foufoula-Georgiou (1993), which found that river network extent controls the response of catchments to precipitation (melt in our case).~~ To illustrate the strong potential~~ly~~ dynamism of supraglacial stream/river network extent on bare ice, Figure 6 presents dynamic supraglacial stream/river networks of IDC1 under different channel initial A_c thresholds (proxy for time). Numerous small supraglacial streams are generated when A_c is set to 5000 m^2 (Figure 6a), while only large main stem channels are obtained when A_c is set to 10^6 m^2 (Figure 6d), yielding drainage density varying from 19.3 m^{-1} to 0.8 m^{-1}. Such strong, seasonal variation in supraglacial stream/river network extent is well-supported by previous high-resolution remote sensing studies, which report similar expansion and contraction of actively flowing supraglacial stream/river networks during the melt season (Smith et al., 2015;Smith et al., 2017;Yang et al., 2018).

Well-developed supraglacial stream/river networks (e.g., simulated using A_c = 100 m^2) route surface meltwater efficiently (Smith et al., 2015), yielding high UH and moulin discharge peaks, whereas relatively poorly-developed supraglacial stream/river networks indicate relatively slow routing of meltwater in expanding interfluve zones (Yang et al., 2018), yielding smaller and delayed UH and moulin discharge peaks (Figures 2g and 2h). As such, temporal evolution of supraglacial stream/river networks substantially alter surface meltwater routing processes and yield dynamic unit hydrographs and moulin discharges. This result is consistent with Montgomery and Foufoula-Georgiou (1993) and van Meerveld et al. (2019), which found that river network extent controls the response of catchments to precipitation (melt in our case). During the first 10 days (240 hours), the channel initiation thresholds A_c are small so numerous supraglacial streams/rivers are developed; thereby, the dynamic A_c RWF routing performs similarly with SUH, 2 m SRLF, and the original RWF. As supraglacial stream/river networks shrink (i.e., A_c becomes larger), our simple modelling experiment (by increasing A_c thresholds every 5 days for the month of July 2015) suggests a gradual dampening of diurnal variations until, by the end of the month, such variations are ~50 % smaller than the same routing method using a smaller A_c value (Figure 2h). Moreover, the average two-day cycle of moulin discharge simulated by the dynamic A_c RWF routing is considerably dampened compared to those simulated by SUH, 2 m SRLF, and the original RWF (Figure 6). In the dynamic A_c RWF routing, the dampening effect displayed in the moulin discharge inputs carries over into the resulting effective pressure cycles as well (Figures 3 and 6).

3.4 Effects of DEM spatial resolution on surface meltwater routing

RWF routing is largely unaffected by DEM spatial resolution, but SRLF routing is significantly affected. Resampling 2 m ArcticDEM data to 5 m and 10 m yields similar RWF UHs and moulin discharges (Figures 2e and 2f), but progressively smoother versions using SRLF UHs (Figures 2c and 2d). At 90 m resolution, SRLF UH shapes exhibit diminished and delayed peaks (Figure 2c). For IDC1, for example, use of a 90 m DEM yields a ~0.10 UH peak at hour 9 and a ~0.04 UH peak at hour 17, whereas 2 m DEM yield a ~0.15 UH peak at hour 5 with all meltwater evacuated within 15 hours.

SRLF applied on higher-resolution DEMs yields larger peak moulin discharges and diurnal discharge signals (Figure 2d). For IDC1, SRLF-routed peak moulin discharge derived from 2 m DEM is 52.4 % larger than that from 90 m DEM, while the corresponding value for SRLF-routed diurnal discharge range is 179.0 %. This finding indicates that SRLF performance is strongly controlled by DEM spatial resolution, with coarser resolutions resulting increased damping of simulated moulin hydrographs. The dampening effect of SRLF moulin discharge induced by DEM spatial resolutions carries over into the resulting effective pressure cycles as well (Figure 3b), urging caution when using coarse-resolution DEMs to route surface meltwater and to simulate subglacial effective pressure.

4 Discussion

4.1 Implications of surface meltwater routing method inter-comparison

This study ~~conducted~~ conducts an inter-comparison of three surface meltwater routing models (SUH, SRLF, and RWF). Due to the lack of field-measured moulin hydrographs, it is difficult to determine which surface meltwater routing model performs most realistically over large areas and long times~~in a wide area during a long time period~~. However, our simulations of moulin discharges (Figures 2, and S1-S4) can provide some insightful information to qualitatively evaluate the performance of certain routing methods. First, inclusion of surface meltwater routing introduces lower peak moulin discharges and delayed time to peak relative to the RCM instantaneous runoff. Second, for IDCs with similar areas and elevations as those examined here, simulated peak moulin discharge consistently occurs between 19:30 and 22:00 (Chandler et al., 2013;Smith et al., 2017). The timing of peak discharge suggests that several routing scenarios are unlikely to be realistic, including any technique that uses unmodified RCM outputs ~~alone~~ as ~~it~~ these values qualitatively underestimate~~s~~ peak discharge time~~, and SRLF using high (2 m) and low resolution (30 & 90 m), due to both underestimating and overestimating peak discharge time, respectively~~.

Additionally, we can use observations of channelized subglacial pressure to strengthen our qualitative comparison. While exact field measurements are not available for direct comparison to our modelled effective pressures, limited field observations indicate that hydraulic head within subglacial channels varies diurnally by at least 40 m and up to 150 m in regions with slightly thinner ice (Cowton et al., 2013;Meierbachtol et al., 2013;Andrews et al., 2014). Furthermore, these reported pressure variations in channelized regions do not fall below 40% of overburden at the observed points. While somewhat influenced by the particular geometry, moulin inputs, and other parameters used, ~~Our~~ our model results for effective pressure in the vicinity of a moulin show modelled mean effective pressure variations ranging from ~2 MPa to ~4 MPa for IDC1 (~26% to 50% of overburden pressure). The RCM runoff produces effective pressures with the largest amplitude fluctuations, and is ~~the single-moulin tests, while somewhat dependent on chosen parameterizations, suggest that~~

~~both RCM only and 2m SRLF do not apply enough delay to ice surface meltwater routing, resulting in modeled effective pressure variations of up to 4.5 MPa in IDC1 (corresponding to ~600 m variation in head; Figure 3f). Combined, these observations suggest that simultaneous RCM runoff is~~ unlikely to provide physically realistic ice surface runoff and the resolution of SRLF needs to be carefully chosen to generate realistic diurnal meltwater inputs to the subglacial drainage system.

Moreover, SUH and RWF both rely on several empirically parameters (C_p and C_t for SUH, and v_h and v_c for RWF) calibrated from a moulin hydrograph measured at the Rio Behar catchment, southwestern GrIS during a very short time period (72 hours), July 2015 (Smith et al., 2017). SRLF is applicable over large spaces and long times because it only relies on DEM to calculate meltwater flow velocities (Banwell et al., 2012). In this study, we assume these empirically parameters are transferable over space and time but this assumption needs further validation. It may hold for ice sheet surface with similar hydrologic and glaciological environments but is problematic to apply over large spaces and long times due to evolving ice surface characteristics. Multiple independent, long-term moulin hydrographs will help eliminate the need for this assumption.

4.2 Influence on diurnal subglacial pressure variations

Our results demonstrate that the routing models and DEM resolution can modulate the diurnal variability of both surface meltwater transport and associated moulin inputs (Figures 3 and 4). Surface meltwater routing alters hourly inputs, with only slight changes to total integrated daily moulin input. However, hourly variations in moulin discharge can influence ice dynamics. Diurnal variations in subglacial pressure, for example, are directly associated with diurnal variations in ice velocity, which have the capacity to induce additional surface-to-bed connections (Carmichael et al., 2015;Hoffman et al., 2018). The diurnal amplitude of moulin discharge also affects the transient evolution of the subglacial drainage system without sustained input to maintain efficient drainage channels, ~~subglacial~~ effective pressure ~~increases~~decreases, resulting in increased sliding velocities, potentially influencing seasonal ice displacement (Hewitt, 2013;van de Wal et al., 2015). As such, including the diurnal signal of moulin discharge may be important for accurately modelling surface-to-bed meltwater connections (Figure 3 & S1-S3). As we see reflected in both the magnitude of effective pressure diurnal amplitudes (Figure 3) and in the timing of minimum/maximum effective pressure relative to moulin inputs (Figure 5), different surface routing methods yield a range of diurnal behaviour. However, as described in Section 3.2, the temporal mean effective pressure produced in our subglacial hydrology simulations with inputs from the various routing models is relatively consistent between routing models. Depending on the time scale of interest, diurnal inputs may not be vital to capture the relevant ice dynamics.

Many subglacial hydrology models commonly invoke a numerical term (the “englacial void ratio”) to represent englacial storage in order to provide short term storage and release of meltwater that cannot be accommodated rapidly within the subglacial system, in the absence of more realistic representation of supraglacial and englacial storage (Hewitt, 2013;Werder et al., 2013;Hoffman et al., 2016). In SHAKTI, this englacial void ratio is also included as an option (Sommers et al., 2018), but our simulations considered here do not employ this term in the equations. Our results demonstrate that the supraglacial hydrologic system ~~can~~ acts as short-term storage for surface-derived meltwater, as exhibited by the time lag of moulin inputs between models; therefore, application of an appropriate surface meltwater routing scheme may reduce the dependence of some subglacial models on a somewhat arbitrary englacial storage term to produce realistic diurnal effective pressure variations and timing lags (Werder et al., 2013;Hoffman et al., 2016). The assumption of surface inputs being instantaneously delivered to the subglacial system is an approximation that ignores the largely uncertain complex flow paths through the englacial system from surface to bed, but it is reasonable to assume that variability in surface inputs should influence variability in inputs to the subglacial system.

Supraglacial routing delays can affect the amplitude and timing of subglacial pressure variations (Figures 3 and 6). While there is limited evidence that within a fully coupled ice dynamics/subglacial hydrology model that diurnal variations in effective pressure can contribute to changes in ice dynamics (Hewitt, 2013), the evolution of the supraglacial hydrologic system can substantially alter effective pressure on diurnal timescales (e.g. Figure 3d). Subglacial channel development is key to terminating early melt season accelerated sliding (Hoffman and Price, 2014) and subglacial channelization occurs more readily and persistently under constant supraglacial meltwater inputs (Schoof, 2010;Poinar et al., 2019). The appropriate choice of a time evolving surface meltwater routing scheme may, in addition to providing the best representation of diurnal effective pressure variations, result in an improved representation of subglacial evolution and improve quantitative representation of seasonal variations in ice flow in coupled models. Our results, however, show that while meltwater inputs with highly variable diurnal amplitudes yield effective pressures with highly variable diurnal amplitudes, the general channelization behaviour and mean effective pressure over the 31-day simulations are quite similar across routing models. Further work is needed to explore the implications of using sub-daily inputs versus time-averaged inputs on long-term subglacial hydrology and ice dynamics in realistic, large domains. The case may be that the peaks and troughs of large-amplitude diurnal input variations effectively ~~even themselves~~balance out to yield equivalent results as time-averaged inputs.

4.3 Influence of seasonal supraglacial drainage evolution on meltwater routing

Seasonal evolution of ice surface drainage pattern can substantially alter surface meltwater routing and moulin discharge characteristics (Figures 2 and S1-S4). Such changes also involve the removal and deposition of ~~the~~ a winter snowpack (Nienow et al., 2017) and the development of a weathering crust on base ice (Cooper et al., 2018), both of which can reduce the prevalence of open-channel flow (Yang et al., 2018). While these processes cannot be explicitly represented with the meltwater routing parameterizations described here, time evolving UHs can integrate the impact of seasonal changes in the relative proportions of porous and open-channel flow. As such, the relative ease of creating dynamic UHs to mimic seasonal evolution of supraglacial stream/river networks is a distinctive advantage of RWF (Figures 2g and 2h).

The development of time varying UHs provides an opportunity to simulate dynamic moulin discharges (Smith et al., 2017;Yang et al., 2018). Such time-varying UHs could be ~~critical in~~important to realistically modelling the evolution of the subglacial drainage system and the development of subglacial channels – a limited supraglacial stream/river extent will dampen the diurnal range of meltwater inputs into the subglacial system and maintain a more constant subglacial pressure (e.g. Figure 3d), which in turn results in less variation in ice motion. Furthermore, limiting diurnal variations may result in more rapid growth of subglacial channels early in the melt season (Schoof, 2010;Hewitt, 2013), thus, potentially produce a more realistic transition to primarily channelized drainage (Banwell et al., 2013;Banwell et al., 2016).

4.4 Impact of DEM resolution on supraglacial meltwater routing

Analysing the influence of DEM spatial resolution on the hydrological response of catchment to precipitation is an important research topic in terrestrial hydrology (Zhang and Montgomery, 1994;Hancock et al., 2006). We expand it to ice sheet hydrology and attempt to investigate the impact of DEM spatial resolution on the hydrological response of supraglacial catchment to surface melt. We found that RWF routing is not affected by DEM spatial resolution, whereas SRLF routing is (Table 2 and Figure 2). The 5 m SRLF UHs and resultant moulin discharges best match with RWF and SUH simulations (Figures 2). This is consistent with the finding that "the most appropriate DEM grid size for topographically driven hydrologic models is somewhat finer than the interfluve scale identifiable in the field" (Zhang and Montgomery, 1994). This behaviour occurs because a coarser-resolution DEM represents bare ice surface topography more smoothly and yields lower bare ice surface slopes, similar to terrestrial topography (Zhang and Montgomery, 1994); lower topographical slopes yield smaller velocities via Manning's open-channel equation.

Different meltwater routing velocities control the meltwater transport time because meltwater flow length is ~~only slightly~~minimally impacted by DEM resolutions. As a result, lower SRLF meltwater routing velocities induce longer meltwater transport time and distribute diurnal surface runoff more smoothly over time (Figures 2c and 2d), whereas stable flow length contributes to RWF's better performances under different DEM resolutions (Figures 2e and 2f).

4.5 Future research directions of surface-to-bed meltwater connection

A challenge remaining unsolved is to map or simulate seasonal evolution of supraglacial stream/river networks. Spatial extent of supraglacial stream/river networks determine partition of interfluve and open-channel zones and thereby controls IDC hydrologic response to surface melt. Moreover, all three routing models described in this study do not explicitly include complex ice surface composition and transformation, including the retreat of seasonal snow cover (Hubbard and Nienow, 1997) and the modification of the ice surface by incoming solar radiation and other processes in the interfluve zone (Karlstrom et al., 2014;Cooper et al., 2018). This may lead to uncertainties in ~~UH~~ unit hydrograph and moulin discharge simulations. Recently, weathering crust has been found to be widely distributed on the Greenland ice surface (Cooper et al., 2018), rather than impermeable bare ice layer as previously assumed (Arnold et al., 1998). Therefore, an appropriate parameterization of porous media flow may be important to accurately describe meltwater transport in the interfluve zone of ice surface (Karlstrom et al., 2014;Cooper et al., 2018;Yang et al., 2018). Additionally, the hourly MAR runoff is a cumulative runoff on one hour and may induce a potential delay of one hour in the peaks; therefore, 10-15 minute ~~MAR~~ runoff outputs ~~should~~ could be used to better capture runoff delays in future.

Furthermore, the subglacial hydrology~~single-moulin~~ simulations in this study should be interpreted as a focused view into how different meltwater routing methods influence local subglacial hydrology in the ~~immediate~~ vicinity of moulins through variations in moulin inputs. ~~Simulations using real surface and bed topographies, moulin locations, and the full IDC areas~~ Regional simulations covering multiple IDCs in a fully coupled ice dynamics~~/~~-subglacial hydrology model remain for future work, an important next step in understanding the surface-to-bed meltwater influence on regional and large-scale ice dynamics. A more direct comparison of model results with observations will be appropriate for this future work, in which the entire drainage catchments are modelled with ~~realistic topography and~~multiple moulin ~~distribution~~ distributed in areas where borehole observations are available or relevant quantities may be inferred from radar products (Chu et al., 2016).

5 Conclusions

Surface meltwater routing is crucial for understanding the surface-to-bed meltwater connection of the Greenland Ice Sheet but remains poorly studied to date. This study presents a first inter-comparison of three different meltwater routing models and employs a subglacial hydrologic model to explore the impacts of their differences on subglacial effective pressure (ice pressure – water pressure) in the vicinity of moulins. Results show that inclusion of surface meltwater routing introduces significantly small peak moulin discharges and delayed time to peak relative to the RCM instantaneous runoff. Different surface meltwater routing models, as well as different spatial-resolution DEMs and seasonal evolution of the supraglacial stream/river networks, induce variable diurnal moulin discharges and effective pressures, which influence ice sliding velocity. While the different routing models produce different diurnal amplitudes in effective pressure variation, the overall channelization behaviour and temporal mean effective pressures are relatively consistent across surface meltwater routing models. Together, these findings urge caution for better representations of surface meltwater routing and moulin discharge simulations to drive subglacial hydrology and ice dynamics models, as well as highlight the need for further research to investigate the cumulative effects of diurnal inputs to the subglacial drainage system and the relevant impacts on ice dynamics.

Data availability

The ArcticDEM data are available at the Public HTTP Data Repository of Polar Geospatial Center at the University of Minnesota (https://www.pgc.umn.edu/data/arcticdem/). Hourly MAR (Modèle Atmosphérique Régionale) 3.6 model data can be accessed by contacting Xavier Fettweis (xavier.fettweis@uliege.be). Codes used to generate surface routing are available via https://doi.org/10.6084/m9.figshare.11635932.v1. The SHAKTI subglacial hydrology model is freely available as part of the Ice Sheet System Model (https://issm.jpl.nasa.gov/).

Author contributions

KY and AS designed the study. KY and AS performed the data analysis. KY wrote the paper with contributions from all authors.

Competing interests

The authors declare that they have no conflict of interest.

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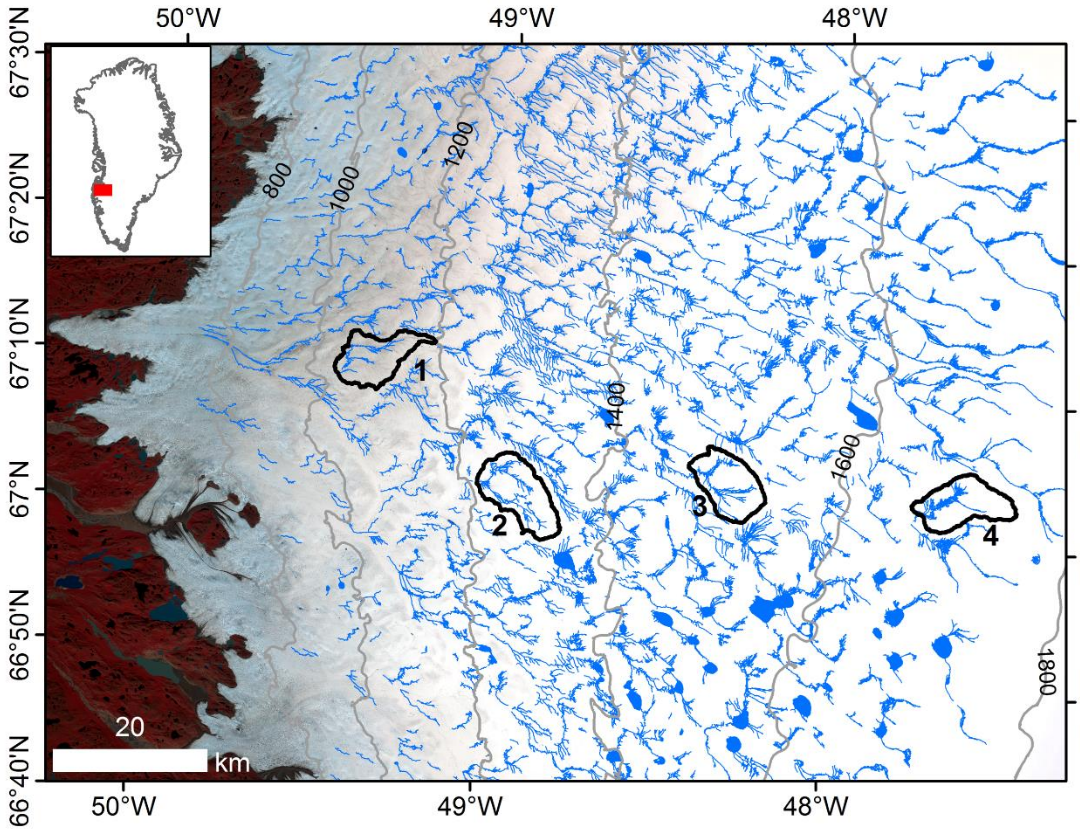

Figure 1. Four supraglacial internally drained catchments (IDCs) on the southwest Greenland Ice Sheet were selected for inter-comparison of surface meltwater routing models. IDC topographic boundaries (black lines) are extracted from high-resolution (2 m) ArcticDEMs. Supraglacial river networks and lakes (blue lines) are mapped from a Landsat-8 panchromatic image (Yang and Smith, 2016). Base map is 10 m Sentinel-2 image acquired on 30 July 2018.

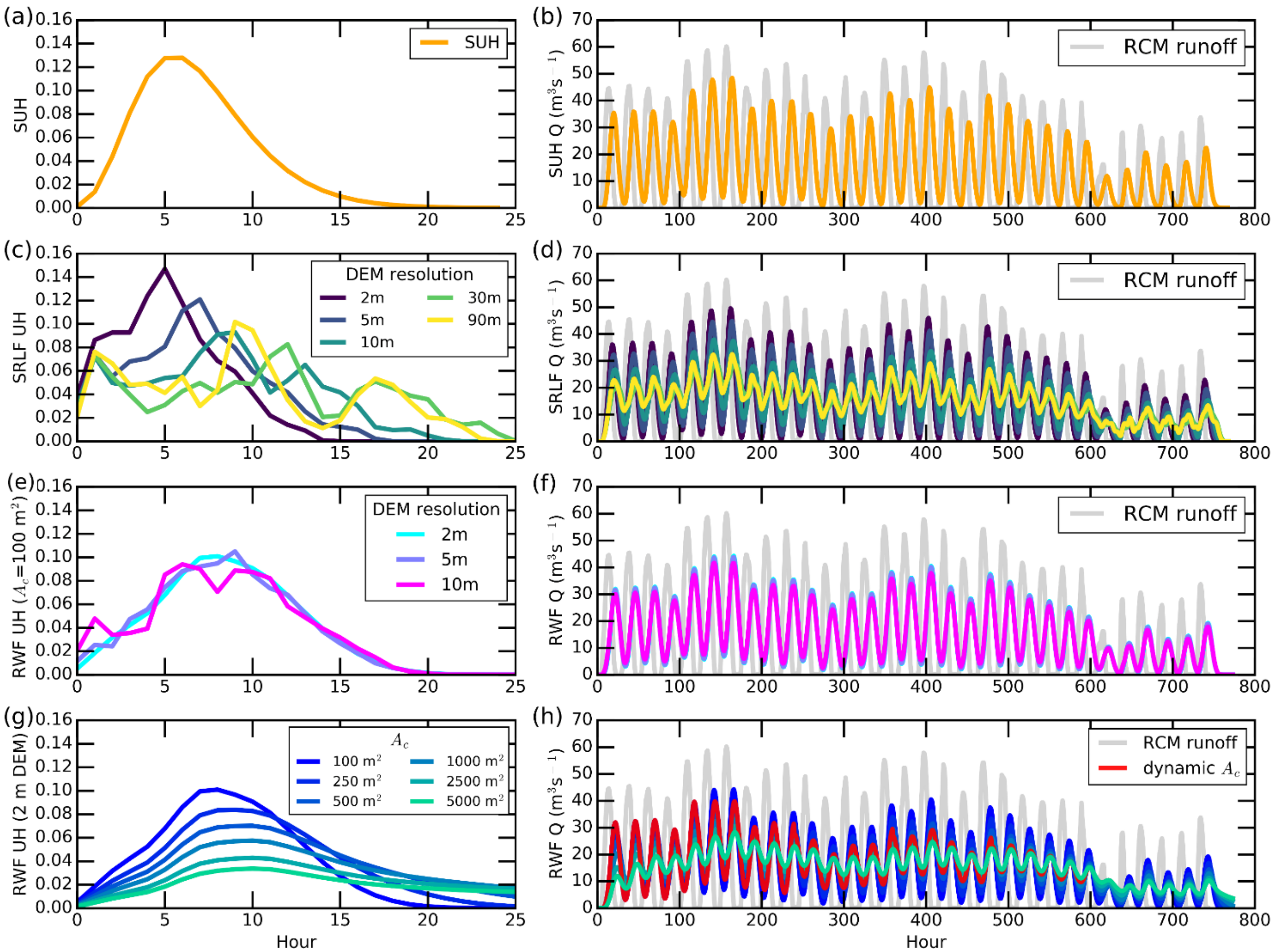

Figure 2. Presentation of Unit Hydrographs (UHs) (column 1) and moulin discharges (column 2) of IDC1 during July 2015, as simulated by three surface meltwater routing models (SUH, RWF, and SRLF). A_c is the cumulative contributing area required to initiate a supraglacial meltwater channel and dynamic A_c values are used as proxy for time to simulate the temporal evolution of supraglacial stream/river networks. Simultaneous RCM runoff (grey line) is shown to indicate the effect of surface meltwater routing process on moulin discharge.

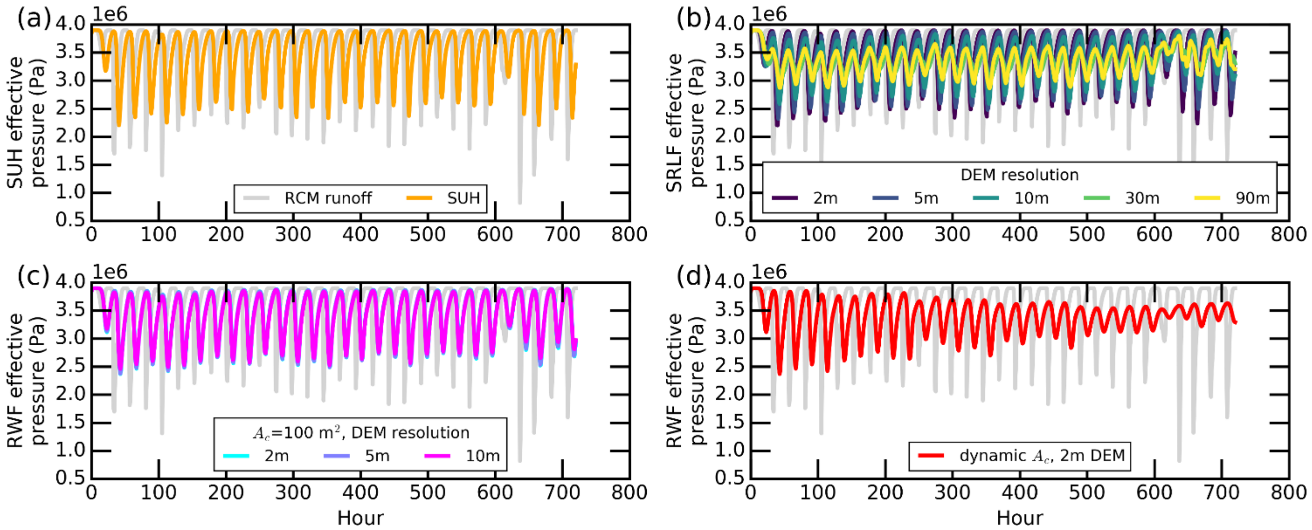

Figure 3. Subglacial effective pressures for IDC1 as simulated by SHAKTI, with inputs to the subglacial system via a single moulin prescribed by the moulin discharges (shown in Figure 2) generated by the various surface meltwater routing models. The effective pressure shown is the spatial mean over the entire 1-km square domain which contains the moulin input at its center.

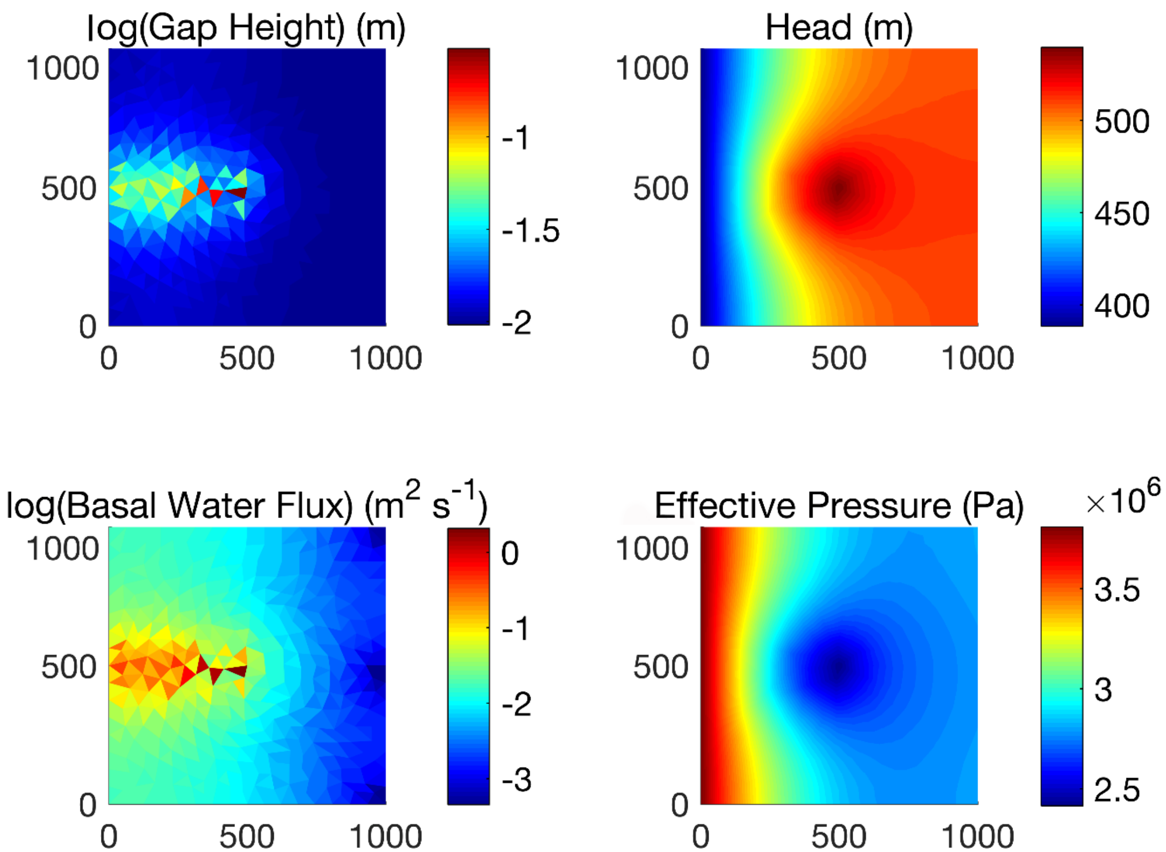

Figure 4. Snapshots of subglacial hydrology fields on day 23 in IDC1 using the SUH routing method to drive moulin input (see full animation of channel evolution and fluctuation in the supplement). An efficient channelized drainage pathway develops from the moulin location at the center of the domain to the outflow at the left, characterized by higher gap height, water flux, effective pressure, and lower hydraulic head than its surroundings perpendicular to flow~~in the y direction~~.

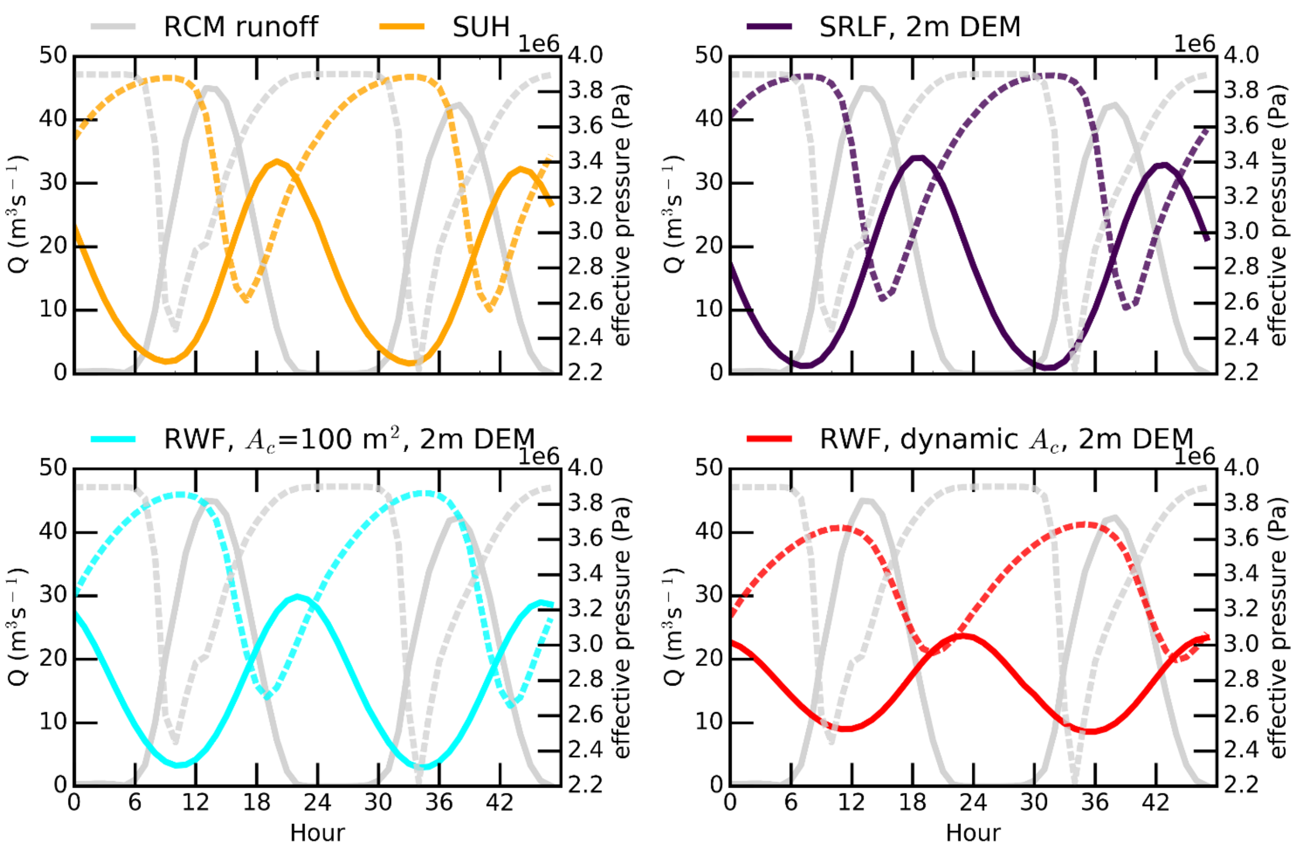

Figure 5. The average two-day cycle of moulin discharge (*Q*) for IDC1 during July 2015 derived from Figures 2 and 3. The daily minimum input in supraglacial moulin discharge (solid lines) corresponds generally to maximum effective pressure (dashed lines), and is followed within 8-9 hours by the daily minimum effective pressure (maximum subglacial water pressure)~~(dashed lines)~~. This suggests that the system shuts down due to creep with low meltwater input, and becomes highly pressurized as meltwater input increases again~~becomes highly pressurized with low input as the subglacial gap shuts down due to creep, then opens up due to melt as discharge increases again~~. ~~-~~As the new water inputs are accommodated, efficient pathways reform and effective pressure increases (subglacial water pressure decreases).

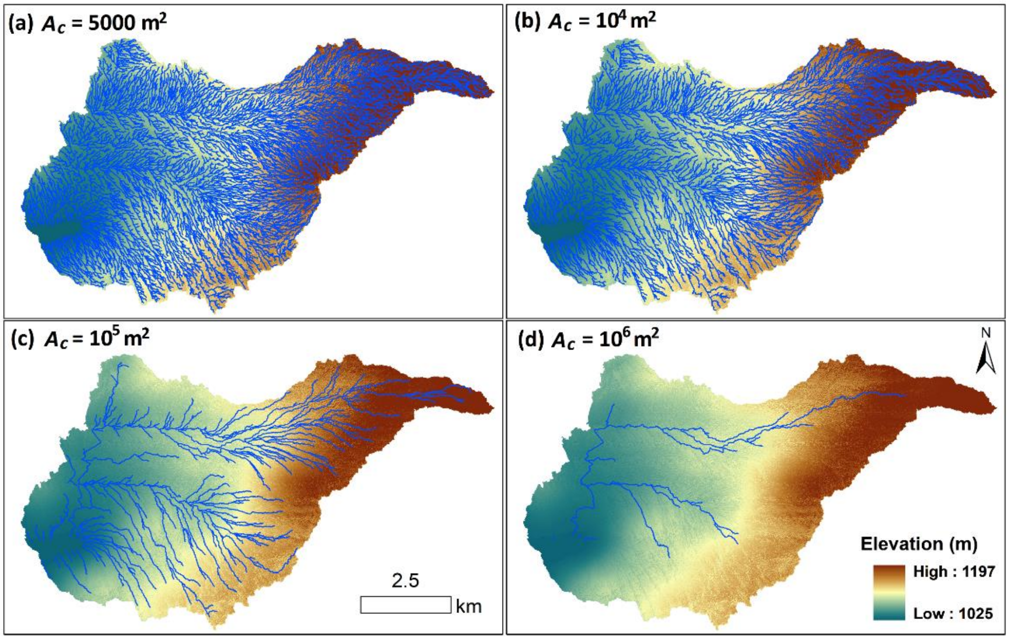

Figure 6. Variable supraglacial stream/river network for IDC1, as simulated by applying variable accumulative area threshold (channel initial threshold, A_c) values to ArcticDEM.

Table 1. A brief summarization of surface meltwater routing models.

Model	Meltwater Routing	Applicable on bare ice surfaces		Applicable on snow surfaces	Parameter dependency	DEM dependency	Case study
		Interfluve	Open-Channel				
Instantaneous RCM runoff	No	-	-	Yes	No	No	(McGrath et al., 2011;Bartholomew et al., 2012;Rennermalm et al., 2013;Fitzpatrick et al., 2014)
Snyder Synthetic Unit Hydrograph (SUH)	Yes	-	-	Yes, but model parameters need recalibration	C_p, C_t are calibrated using a field-measured moulin hydrograph	No	(Smith et al., 2017)
Surface Routing and Lake Filling (SRLF)	Yes	No	Yes	Yes	No	DEM is required to calculate meltwater flow velocities for all catchment cells	(Arnold et al., 1998;Willis et al., 2002;Banwell et al., 2012;Banwell et al., 2013;Arnold et al., 2014;Banwell et al., 2016;de Fleurian et al., 2016;Koziol and Arnold, 2018)
Rescaled Width Function (RWF)	Yes	Yes	Yes	Yes, but model parameters should be recalibrated	Interfluve and open-channel flow velocities (v_h and v_c) are calibrated using a field-measured moulin hydrograph	High-resolution (<10 m) DEM is required to calculate interfluve flow path length	(Yang et al., 2018)

Table 2. Summary of four study catchments.

Catchment ID		IDC1	IDC2	IDC3	IDC4
Area (km^2)		53.0	66.9	57.3	58.5
Mean Elevation (m)		1054	1248	1473	1646
Mean surface slope (m/m)		0.018	0.020	0.008	0.008
Mean bed elevation (m)		207	309	247	222
Mean bed slope (m/m)		0.050	0.075	0.036	0.022
Mean ice thickness (m)		847	939	1226	1424
Mean ice flow velocity (m/a)		116	99	98	73
Distance to ice edge (km)		25	40	70	100
Peak discharge time	RCM	13-15	13-15	13-14	13-14
	SUH	19-20	20-21	19-20	19-20
	SRLF 2m, 5m, 10m, 30m, 90m	18-19, 20-21, 21-22, 22-23, 22-23	18-19, 19-20, 21-22, 21-22, 21-22	17-18, 18-19, 20-21, 22-23, 22-23	17-18, 19-20, 23, 23, 23
	RWF	22-23	21-22	20-21	21-22

Table 3. Constants and parameters used in subglacial hydrology simulations.

Symbol	Value	Units	Description
ρ_w	1000	kg m^{-3}	Bulk density of water
ρ_i	910	kg m^{-3}	Bulk density of ice
A	5×10^{-25}	Pa^{-3} s^{-1}	Ice flow-law parameter
n	3	Dimensionless	Ice flow-law exponent
b_r	0.1	m	Typical height of bed bumps
l_r	2.0	m	Typical spacing between bed bumps
g	9.8	m s^{-2}	Gravitational acceleration
ω	0.001	Dimensionless	Parameter controlling nonlinear transition between laminar and turbulent flow
L	3.34×10^5	J kg^{-1}	Latent heat of fusion of water
G	0.05	W m^{-2}	Geothermal flux
c_t	7.5×10^{-8}	K Pa^{-1}	Change of pressure melting point with temperature
c_w	4.22×10^3	J kg^{-1} K^{-1}	Heat capacity of water
υ	1.787×10^{-6}	m^2 s^{-1}	Kinematic viscosity of water
e_v	0	Dimensionless	Englacial void ratio