Author Response to RC1 for “Brief communication: The Impact of Interannual Melt Supply Variability on Greenland Ice Sheet Moulin Inputs”

Tim Hill & Christine F. Dow

Reviewer Comment	Author Response

General Comments

In this paper the authors apply their Subaerial Drainage System (SaDS) model (Hill and Dow 2021), a supraglacial meltwater routing model, to a ~20 km^2 area for four melt seasons to assess how the supraglacial drainage system and moulin discharge changes between years with high and low melt intensities. At present there is not a description of the SaDS model in the manuscript or in the supplement which prevents the readers from understanding the physics of this approach without referring to the other manuscript. Further, there are no comparisons of the model to any observations over the four years considered here, without any description of model validation it is hard to determine if the results are physically meaningful. At present the paper’s main findings are unclear. I do see potential in the work presented here, however, major revisions are required to address the structural and clarity issues and further develop the ideas presented for readers to understand or have confidence in results and conclusions derived from this work.

We appreciate the reviewer’s comments and suggestions. The concerns raised here are addressed individually below, followed by a high level plan to address both reviewer’s comments about structure and clarity (**General Changes**).

Specific Comments

1. The manuscript currently lacks any real description of the model, a more thorough description needs to be included in the main text with supporting details in the supplement. The results and discussion mention several model parameters which are never introduced, explained or justified (e.g., sheet mass, channel mass, lake depth, and incised channel length/channel incision depth with no figures that correspond to the details stated in the results).

The current manuscript intentionally did not fully describe the model in terms of its governing equations and parameters since this description is presented in detail in Hill & Dow (2021). However, to address this concern we have written an Appendix summarizing the key model equations, and we will describe the relevant mechanisms in the Introduction.

Specific model parameters (Table S2) are not discussed in the main text. We believe the descriptions of model outputs (e.g., sheet mass, channel mass, and their associated units etc.) are sufficiently accessible that they do not need to be described in detail with reference to the relevant governing equations from Hill & Dow (2021). If necessary, readers will be able to refer to the appendix for more details.

2. The structure of the manuscript needs some reworking. For example a majority of the paper is framed to focus on the timing of meltwater delivery to moulins and how this evolves over the melt season, however, a majority of the discussion focuses on supraglacial lakes, introducing Figure 3 that is not included in the Results section or described in the methods, and then does not mention lakes again in the conclusions. Similarly the end of the discussion compares the SaDS model to other modeling works that are not mentioned in the introduction, much of this content should be moved to the introduction to explain why this model is being used, what makes it unique, and how it differs from other models.

We agree that the focus of the paper was inconsistent between sections. See the **General Changes** section below for our proposal to restructure the manuscript.

3. There are many ideas and concepts that are either not introduced and come out of nowhere or that are briefly discussed but never resolved. (i) The paper focuses on seasonal trends in drainage system behavior however Section 4.1 is very brief and makes several statements without a robust discussion. There are several statements that are unsupported such as that decreasing moulin diurnal amplitude is caused by the extent of the supraglacial channel network, however, there are no figures that show supraglacial channel network evolution.
As part of the **General Changes** we plan to make, we will remove unsupported statements (e.g., decreasing moulin diurnal amplitude is caused by changes in the channel network), and instead focus on the lack of smooth, continuous trends in amplitude and time lag in most years. As with Muthyala et al. (2022), we observe distinct changes in lag time and diurnal amplitude related to changes in melt rate.

What are the errors associated with your lag times and the ones presented by Muthyala et al? How does this factor in to the comparison you present?
Based on tests with different interpolation methods, the error in lag time related to the linear interpolation scheme applied to RACMO runoff data is small (0–0.5 hours). See also our response to the L65–68 comment. The limitations of using RACMO runoff outputs are one reason we have not applied SaDS to the domain of Muthyala et al. (2022) for a direct comparison. Without in-situ melt forcing data at sufficiently high temporal and spatial resolution, it would be difficult to disentangle discrepancy arising from incorrect melt forcing from discrepancy related to the SaDS model. However, given the lack of in situ melt data available for much of Greenland, we believe our approach using RACMO is justified in the broader modelling context. We now discuss the limitations of our linear interpolation scheme and more generally the limitations of using RACMO data in the manuscript in section 2.3.

Also, this section states that the lack of a trend is because of the domain size and number of supraglacial lakes, how these two things would affect moulin discharge and diurnal amplitudes should be discussed and cited.

We will update this comparison to include the two most similar sub-catchments within our domain, which have similar stream discharge (< 1 $m^3 s^{-1}$) and do not contain supraglacial lakes to remove the unsupported statements related to catchment size and the influence of lakes. We have found that the smaller catchments without supraglacial lakes result in moulin inputs with higher diurnal amplitudes and shorter lag times.

Further, this section puts this work in the context of only one other paper Muthyala et al., 2022, and does not mention other studies (e.g., Yang and Smith 2016, Yang et al., 2018, Smith et al., 2021). It would be interesting to know how these model results relate to the wider supraglacial drainage system literature.
The model results are compared to the wider literature in Section 4.4. In this section we only compare to Muthyala et al. (2022) since it is the only study with a sufficiently long discharge timeseries to observe seasonal trends in discharge amplitude and timing. Smith et al. (2017) and Smith et al. (2021), for example, only present discharge records for 3–7 days and we are primarily interested in differences between years. We will explain this reasoning in the manuscript. The SaDS outputs were compared against Yang et al. (2018) in Hill and Dow (2021) and we refer readers to this in the manuscript.

(ii) Section 4.2 is missing a description of differences in the timing of meltwater delivery to moulins with catchments that either have or do not have supraglacial lakes. What were the differences that the model produced?
Following the **General Changes**, this section will be updated to include an assessment of the controls on moulin discharge for the small catchments without supraglacial lakes. The primary findings are that the three small catchments in our domain without lakes have shorter lag times and larger diurnal amplitudes than the four large catchments with supraglacial lakes.

(iii) There is no discussion of where the lake depth measurements are coming from, no discussion that justifies or explains why this model allows lake level to rise meters above the maximum lake surface.
We will make it clear that the lake depth measurements are derived from the model outputs. The “overfilling” of lakes is due to water flooding the lake drainage pathway, particularly for L1 which lies in a deep trough with low slope (L144-145) (e.g., Chudley et al., 2019). We now discuss the benefits that performing future in situ measurement of lake depth and outlet drainage path incision would have for model validation. Unfortunately these data are not currently available for this study site.

4. Lack of comparison with data to show that the model is actually physically representative of ice sheet evolution. A description of how the model was validated would add credibility to the results presented in this manuscript. At present it is unclear if these results are physically meaningful.
Hill & Dow (2021) present an indirect comparison to a satellite-derived drainage system map (Yang & Smith, 2016). The authors are not presently aware of a dataset(s) containing stream discharge measurements for the entire melt season covering the range of stream discharges presented here (<1 $m^3 s^{-1}$ to >50 $m^3 s^{-1}$). This makes it difficult to validate the model. The most

appropriate dataset is that presented in Muthyala et al. (2022). However, this dataset would only allow validation of the model for small streams, which have distinct behaviour from the large rivers that dominate our study site. Smith et al. (2021), for example, provide 168 hours of measurements for a larger river (5.75 to 37.61 $m^3 s^{-1}$). However, this dataset is not appropriate to constrain seasonal changes in the drainage system, which is the primary intention of the SaDS model. We hope that our work demonstrating the importance of seasonal surface drainage evolution will encourage collection of long-term data sets and we point this out in the manuscript in section 4.4.

5. Repeated use of imprecise language, some examples below:

L11 controls on mass loss are vague and glossed over, this important topic warrants specifics
We agree that this topic is important. However, since the current work does not directly address controls on mass loss, it would be misleading to focus on the controls on mass loss. See below (**General changes**) for our plan to restructure the Introduction to focus on the most relevant background material.

L16 "…can improve the efficiency", the concept of drainage system efficiency has not been introduced and the phrasing "improve efficiency" is not clear
We believe this terminology is sufficiently common in the context of subglacial hydrology to be presented without a complete definition.

L4 of the abstract "the model outputs predict important differences…"
L16 "meltwater to be evacuated at lower pressure", lower than what?
L27 "significantly affect"
L113 "noticeably later", is 4 days noticeable? State 4 days instead
L120 "significant seasonal changes"
L164 "uncorrelated" this needs to be shown, r values and p values needed
L147 "saturate", what does this mean? Consider rephrasing
These examples and the language throughout will be made more precise.

L151 "distributed and channelized systems" this terminology is used here to describe the supraglacial drainage system but it typically reserved for the subglacial drainage system. Further, the components of the supraglacial drainage system are not described in the introduction (I.e., flow through channels vs interfluvial flow). This needs to be rephrased.

We intentionally use this terminology, which the reviewer has correctly identified as borrowed from subglacial hydrology, since we intend to convey the exact same concepts. We will present key model equations in the Appendix and more fully describe the key model structure in the Introduction to give the readers the necessary context. To clarify for the readers, the difference between flow through channels and interfluvial flow has been explained in the Introduction.

Line Comments

23: extreme surface melt events and lake drainages would overwhelm an inefficient drainage system as well.
That is correct, these events with unusually high moulin input rates would result in a transient high water pressure response for any subglacial drainage configuration. As part of the **General Changes**, we are focusing the Introduction more specifically on the supraglacial drainage system, so this statement will be removed.

27: “damp and delay” is introduced here but never referred to again,
This sentence will be reworded into more plain language.

32: lag time between what and what?, also include a citation to Yang 2018, or say “for example”.
Lag time between local solar noon and peak discharge. We will explain this in the text.

55: “triangular computational mesh” is not introduced and is therefore confusing. Consider flipping the order so that your model description is before the data subsection.
We agree this is confusing. We will reorganize this section as suggested, explaining the model before the input data.

65-68: RAMCO melt rate with a 3 hour resolution is downsampled to 20 seconds for the SaDS model run. How does this affect your results? What is the temporal error associated with your lag times? This needs a more thorough discussion
We have tested smoother interpolation schemes to downscale RACMO melt rate to the 20 second model timestep, and there is a minimal change in the timing of peak moulin inputs (0–0.5 hours) and a ~1% change in peak moulin inputs compared to a linear interpolation scheme. We therefore believe the temporal error associated with lag times is small compared with the overall uncertainty arising from using climate model forcing and will explain this comparison and associated uncertainty in the text.

73: Describe what a distributed water sheet is and how this relates to physical flow structures
On the bare-ice surface, the distributed water sheet refers to flow through the weathering crust. We will add this to the model description in the Introduction and in the Appendix where we will present the key model equations.

75-76: This triangular mesh/model domain is not shown in Figure 1 as cited. A figure with the model domain needs to be included in either the manuscript or at minimum in the supplement.
We agree that it was difficult to see the triangular mesh. We have added translucent lines for triangle edges on Figure 1a.

86: Define what you consider a melt event early on in this section, it would make it easier to understand the text and to distinguish from a diurnal melt cycle and a multi-day melt event.
We will make this more precise by referring to specific dates representing archetypal events in the text.

95-100: Change the order of your examples so they are chronological, also what moulin are you referring to? Moulin input values are given but no specific moulin is named.

We will make this more precise. To make the rest of the Results and Discussion more precise, we will assign numeric labels to each catchment, so that moulins and lakes can be explicitly related, and so the text can refer to specific catchments. In this example, we were referring to the moulin downstream from lake L1.

88-89: Here you state that moulin inputs broadly track surface melt with the volume dependent upon catchment size, moulin location and melt volume, citing Figure 2, however, this figure does not show this relationship. There is no quantified or demonstrated relationship between discharge and catchment geometry.

The relationship was not made explicit, but the relationship is qualitatively demonstrated by comparing Fig. 1 & 2. We have defined the catchment boundaries and will add these to Figure 1. We have explicitly quantified the relationship between melt rate within each catchment and the corresponding moulin input, and will tabulate this within the text.

101: Having an amplitude of 100% doesn't make sense, and comparing melting to moulin inputs is similarly confusing. Discharge isn't going to zero because of recession flow. So these two things can't be compared directly.

Throughout the text we refer to the difference between the diurnal maximum and minimum moulin inputs as the diurnal amplitude, and we will add this definition to the text. With this definition, an amplitude of 100% means that the difference between diurnal maximum and minimum moulin inputs is equal to the diurnal mean moulin input. In other words, no surface inputs are provided to moulins overnight when the amplitude is 100%.

Comparing surface melt (i.e., the system's forcing) to moulin inputs (i.e., the system's response) illustrates how strongly reduced the diurnal peak moulin inputs are. We do not claim that we expect moulin inputs to reduce to zero overnight in general. This comparison is especially useful considering that it is an accepted approach to instantaneously route all melt generated within a catchment into the moulin for subglacial hydrology modelling.

146: Cascading lake drainage comes out of nowhere

We agree that this statement is not properly supported or explained and will remove it.

147-150: Lake water level does not affect the timing of hydrofracture. Consider removing this paragraph as it is incorrect.

We are not aware of evidence that the timing of rapid lake drainage is entirely independent of lake water level. For example, Poinar & Andrews (2021) find that variance in the date of fast lake drainage is not fully explained by strain rate variations. A nonzero proportion of the variance in the date of lake drainage is explained by the date of melt onset and cumulative surface melt, which together approximately determine the volume of water stored within lakes. We will therefore make this statement more precise and explain rapid fluctuations in lake drainage as a possible confounding effect, rather than a primary control, on rapid lake drainage.

155-161: Melting of the channel’s base and walls by the flowing water is not discussed in this section. This process is particularly important for the channels draining supraglacial lakes which can incise several meters into the ice.

This mechanism is not discussed here since rapid lake drainage through incision of the outlet channel is not observed in our model outputs, despite the theoretical ability of the model to permit this behaviour. In part, this could be due to the necessary assumption of a fixed width-to-depth ratio for supraglacial channels. We are adding a discussion of physical mechanisms expected to control supraglacial drainage to the introduction, which will include this mechanism. We will point out the possibility of this rapid lake drainage mechanism when we compare SaDS to other drainage models, since the ability to represent this mechanism is a distinguishing feature of SaDS.

169: correlation < 1? This doesn’t make sense

What we intended to say is that not all the variance in moulin discharge is explained by lake depth. We have directly quantified the proportion of variance of moulin discharge explained by lake level to make this statement clear.

178: The other models discussed in this section need to be introduced in the paper’s introduction, at present they come out of nowhere.

As part of the **General Changes**, these models will be presented in the Introduction in order to motivate the comparison.

213: “seasonal decreasing trend in moulin diurnal amplitude”, do you mean moulin inputs? This is a very important distinction that needs to be made as you do not discuss moulin water level at all.

Yes, we mean the diurnal amplitude of moulin inputs. We are not making any statement about the absolute water level within moulins. We will reword this statement accordingly.

218-219: it is not clear that the moulin inputs presented here are realistic.

This is strictly true since we have not directly validated the presented hydrographs. To address this concern, we explain what type of data would be required to validate moulin hydrographs generated with SaDS in section 4.4, where we also qualitatively compare the two small, lake-free sub-catchments within our model domain to the Muthyala et al. (2022) dataset. Despite the lack of direct validation of our moulin hydrographs, the hydrographs contain specific features (lag time, diurnal amplitude) that are in line with observations, indicating that our moulin inputs are more realistic than the common practice to instantaneously route all meltwater generated with a catchment through the terminal moulin.

Figure 1, Outline individual catchments draining each moulin. At present I cannot tell which moulin is draining which lake, or visually compare catchment sizes. There is also not a triangular mesh as cited in the text. Also include a legend. Further, there is no explanation for why only three of the lakes are labeled when in Figure 1a I can see several other lakes within the catchment’s boundaries. What is the pink moulin draining? I do not see any stream flow lines leading to that moulin.

The SaDS model does not explicitly differentiate between individual catchments in the same way as, e.g., the SRLF model (Banwell et al., 2012). We have defined catchments based on the modelled hydraulic potential, and will include the catchment boundaries on Figure 1.

We will add the computational mesh to Fig. 1, and we will make it clear that only the four largest modelled lakes are labelled. The identified moulin receives only very minimal flow (Fig. 2). This moulin is included since it is identified by Yang & Smith (2016), although it is possible it has been misclassified in that dataset.

Figure 2, Add a legend indicating what colors mean. The dashed/dotted line for melt rate is hard to see. Consider either making it solid black or another color. Right now it looks gray. (e.f.) Rename axis to state that the lag time is between solar noon and peak moulin discharge. The colors are very hard to see in general, particularly for (a) and (b), I can hardly tell that there are discharges plotted for pink and yellow moulins close to zero. It is also hard to tell the difference between the teal and green colors. Include which moulins are draining lakes and which are not in the legend as well. The color choice for lakes are also confusing, do the colors correspond with the moulins that drain them? If so, state that.

We have developed a consistent color scheme between lakes and their outlet moulins, and we will add the legend to Figure 2. We have also increased the linewidth for the melt rate curve to make it more visible. It is difficult to plot a two-order-of-magnitude difference in discharges on the same figure (a, b), but we have scaled the amplitude such that the amplitude trends for all seven moulins can be seen for (c, d).

Figure 3, This figure is not introduced until the discussion.

As part of the general restructuring, this figure will be removed in favour of a table quantifying the relationship between surface melt, moulin inputs, the diurnal amplitude of inputs to moulins, the time lag of moulin inputs, and the water level within supraglacial lakes.

Editorial Remarks

L14: Change “This” to “The”
L88: the surface -> the ice surface
L92: "limited short-term (several day) spikes” -> several day spikes
L97: moulin inputs and moulin discharge are used interchangeably, chose one and stick with it
L97: which moulin?

We will make these changes.

General changes

To address the general and specific comments above, and those of Reviewer 2, we propose to revise the manuscript as follows.

Introduction

- Reduce the discussion of the impact of meltwater supply variability on sliding velocity, since this is not directly supported by our work.
- Introduce and describe the models that are currently introduced in Section 4.4.
- The primary goals of the communication will be to:
  - Investigate the detailed modelled drainage behaviour for a catchment containing small catchments without lakes and large catchments with lakes.
  - Quantify the relationship between surface melt and the magnitude, amplitude, and timing of moulin inputs, and between supraglacial lakes and their outlet moulins.
  - Compare SaDS to a range of comparable models from the literature.
  - Define the situations where a process-resolving model may be advantageous and where such a model may not be practical.

Data and Methods

- Switch the order of Section 2.2 (Data) and 2.3 (Model) to describe the model before explaining the data used to drive the model
  - Explain key model mechanisms (e.g., balance between heat dissipation along channels walls and ablation of adjacent ice surface) in more detail in the model description section
  - Summarize the key model equations in an Appendix
- Explain that we model four years with varying melt intensity and melt season durations to capture how drainage behaviour varies with different realizations of melt forcing
- Assign consistent labels between moulins and lakes, and explicitly include these labels in the text when discussing particular catchments, moulins, or lakes

Results

- Use catchment labels to make discussion of particular features more precise
- Quantify relationships that are currently described qualitatively (e.g., computing the proportion of variance of moulin input, lag time, diurnal amplitude, and lag time that is explained by surface melt rate)
- Compare quantities of interest (moulin input, amplitude, lag time) for catchments with and without lakes and quantify the extent to which changes in lake level determine inputs to downstream moulins, and what the controls are for catchments without lakes

Discussion and Conclusions

The Discussion and Conclusions will center around a few questions supported by our Results:

1. What seasonal trends are observed in the modelled supraglacial drainage system? How do these vary with melt forcing?
2. How do supraglacial lakes impact modelled moulin inputs?

3. How do these modelled inputs compare to observations by Muthyala et al. (2022), in particular for our smaller catchments that do not have a supraglacial lake?
4. How does the behaviour we see across years with varying melt forcing compare to what would be predicted with other models? When might it be important to use an expensive process-resolving model, and when might it be appropriate to use a simpler and less computationally expensive model?

References

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