Response to anonymous Referee #1

General Comments:

This manuscript describes the 46 discharge measurements and continuous water level measurements for 62 days during the summer of 2016, which is a long record for in situ supraglacial stream measurements. The manuscript touches on several topics including surface energy budget, the timing of daily maximum discharge, and hydraulic parameterization. The writing is clear and concise. The overall flow is reasonable and easy to follow. However, this manuscript would benefit greatly from more in-depth analyses. Please see my detailed comments below.

1. What's new? I do not mean there is no new information here. However, the take home messages do not strike me as new knowledge. For example, the conclusion of the surface energy balance that shortwave radiation dominates the seasonal and diurnal variabilities of surface melt (and thus runoffs) while longwave radiation and sensible heat contribute more than usual to peak melt events has already been made clear by several previous studies cited by this manuscript. The conclusion of the hydraulic parameter analysis concurs with that of Gleason et al. (2016): hydraulic geometry parameters cannot be generalized. The analysis of the timing of daily maximum discharge was left without a firm explanation. A lack of a clear statement of your novelty would make a reader wonder: what questions can your measurements answer but others cannot? Or what are the questions you intend to answer before starting the measurements? What new knowledge did you gain from presenting these measurements?

Author Reply:
When we revise this manuscript, we will improve the manuscript to add clear statements about the novelty of our study and a detailed introduction to our measurements answering why we collected this data, how do they differ from current available data and what new knowledge did we gain from analyzing it.

Briefly, our revised manuscript will make these points (the text below was also a response to reviewer 3 comments):

i. Novelty of our study
   a) While the conclusion about surface energy balance is not new, our study is unique by using direct measurements of runoff. Previous studies used weather stations and model simulations to estimate melting and compare with surface energy components. We will rewrite the manuscript to make these points clear.

b) While timing of daily maximum discharge has been estimated using in-situ discharge in previous studies, those studies only span a few days. In our study, using 62-days long in-situ stream discharge, we show that this timing of daily maximum discharge changes over the melt season due to varying catchment conditions. This long term record allows us to make assessments of supraglacial stream dynamics that are more substantiated than other studies that may be subject to random variability within the system. More explanation about this change and the processes affecting it will be given in the manuscript to make this clear.

c) The goal of performing the hydraulic geometry analysis was to see how the 660 catchment parameters compare with the previous studies and if they fall into a range of parameters from similarly sized supraglacial streams. Our parameters compare well with the parameters from Knighton (1981) and Marston (1983), but do not match with streams from Gleason et al. (2016). Indeed, we reach the same conclusion as Gleason et al. (2016), i.e that hydrologic parameters cannot be generalized over the Greenland ice sheet. However, we find that our study is a contribution given the extremely small number of similar studies. In other words, part of the novelty is that Greenland supraglacial stream flow observations are extremely rare, and long observations like ours are even more rare. Additionally, hydraulic parameters of supraglacial streams have shown to be highly spatially variable and this study furthers Gleason's conclusions by analyzing streams closer to the ice edge.

ii. Research questions behind the collection of these unique measurements. We will clarify the research questions driving our work in the introduction. These questions include:

   a) How does the supraglacial stream discharge vary over the entire melt season?
   b) What are the drivers of this discharge throughout the season?
   c) Given the findings of a model study by Yang et al. (2018) on how timing and amplitude of daily discharge change with stream network size and evolution, what does the timing and amplitude of discharge suggest about network evolution in our study catchment?
   d) How do the hydraulic geometry parameters of the streams in 660 catchment compare with the previous studies?

iii. What new knowledge did we gain from these measurements?

a) Surface energy balance:

We agree with the referee that previous studies have already shown some of our findings about discharge and surface energy balance. Specifically, previous work has shown that that while shortwave radiation highly contributes to the seasonal and diurnal variation of surface melt, longwave radiation and turbulent heat fluxes have an increased contribution during peak melt events (Van den Broeke et al., 2011, Fausto et al. 2016). However, all these studies rely on model simulated melt using local weather station data. In contrast to these studies, we have direct observations of melt water runoff. In other words, what is new in our study is we specifically use runoff in the streams and explore the drivers influencing the runoff throughout the melt season. We also quantified the dependency of stream discharge over different energy components over different time periods (peak flow days and seasonal average). We will clarify this in the revised manuscript.

b) Timing of daily maximum discharge:

Timing and magnitude of meltwater delivery to the subglacial system can influence subglacial hydraulic pressure and ice velocity. From the previous studies we have seen that this timing varies based on catchment size, however this study adds an additional component by showing that time to peak varies significantly throughout the melt season. This is a novel conclusion and shows that changes in supraglacial network geometry due to increased melt rates and changes in weathering crust hydraulics can influence the conveyance of water to the subglacial environment. In addition, a time series of water level in the weathering crust will be added to the analysis that shows a constant decrease in water stored in the weathering crust coinciding with the decrease in lag between timing of daily maximum discharge and solar noon. Less water stored in the weathering crust could lead to an earlier daily maximum discharge as the melt season progresses. We will clarify the discussion about this novel result in the revised manuscript.

iv. Importance of these measurements:

We will clarify that our dataset fills a huge gap among geoscience dataset. There is only a very small number of similar datasets of Greenland ice sheet supraglacial stream flow data, and only one other dataset, like ours, which covers the majority of the melt season. In other words, there are almost no direct observations of this glacio-hydrological feature. With our unique data, we provide a perspective on the diurnal and daily variation of supraglacial stream discharge over a melt season. For the first time, we can compare direct observations of melt water losses with energy balance drivers of melt, and explore peak discharge timing.

2. Broader impacts From reading this manuscript, I can tell what you measured and how but it is not clear why. I know these new measurements have merits on their own. I bet they are essential for certain questions. But without explicitly stating these questions and broader impacts, it is hard for readers to connect. For example, the potential impacts of the timing of peak discharges on the subglacial system and ice dynamics should be within the scope of this manuscript not in future work. This is the very reason you measured and analyzed it. Another example is from the introduction (Line 35-38): "...only a handful of studies using in situ supraglacial stream discharge to characterize current conditions". A few more words here to state the caveats of not using in-situ supraglacial stream discharge to study surface mass loss would emphasize the significance of this manuscript.

We will revise the manuscript to clarify why we did this work. Also see our response to your previous question where we explicitly state the research questions driving our work. The revised manuscript will include the following points:

a) Why

   We will clarify that a motivation to study supraglacial stream discharge is that the stream discharge is the actual amount of meltwater that is delivered to moulins. As mentioned before, previous studies only examine surface melt (estimated with models and weather station data), which are not affected by processes that influence flow and surface storage of water from when it melts to when it is delivered to the moulin. Recent research has shown that there may be significant disagreement between modeled runoff and in-situ stream measurements (Smith et al., 2017) and therefore applying in-situ measurements of streamflow allows for an analysis of the energy balance components without this potential modeling bias.

   Another motivation is previous work that shows: a) the weathering crust stores water (Cooper et al., 2018) and b) the storage is proportional to solar radiation as windy and overcast conditions with higher longwave radiation reduce the storage capacity with higher longwave radiation (Takeuchi et al., 2000). We will add a new time series of cryoconite water level observations that shows a decrease in water level coinciding with the decrease in lag between time of daily maximum discharge and solar noon. By having both stream discharge and cryoconite water level observations we can better address the question about variable storage of water within the weathering crust over the melt season.

b) Potential impacts on ice dynamics

   We disagree that an analysis of stream discharge and ice dynamics are within the scope of this paper. We hope that we provided better explanations for the motivation and broader impacts of our study as requested by the reviewer (see response above) so it is clear that our paper fills an important gap in our understanding of Greenland ice sheet melt.

c) Caveats of not using in-situ discharge to study mass loss

   In the revised manuscript we will add text to explain what additional knowledge is gained by using in-situ supraglacial stream discharge to study mass loss. To summarize, the main gain of using in-situ discharge is that they provide direct measurements of actual meltwater delivery to moulins by providing both volume and timing. The data can also be used to infer information about surface processes, e.g. temporary storage in weather crust and supraglacial stream network dynamics.

3. Title A study on “seasonal variability” usually includes more than one season of data. The seasonal variability in this manuscript is more like daily or inter-diurnal variability.

Author Reply:
We agree with the reviewer and are considering changing the title to: "Supraglacial in situ streamflow and drivers over 62 days of 2016 melt season in Southwest Greenland".

4. Introduction It would be more beneficial for readers if some of the statements are more specific. For example, in Line 32-34, how does increased surface melt influence ice sheet basal properties and ice dynamics: does surface melt increase or decrease basal melt? Line 49-50, how does timing influence ice sheet velocities?

Author Reply:
We will rework the manuscript and include specific information and remove vague statements. We will rewrite the specific examples mentioned by the reviewer and revise other similar statements

5. Section 2 Study Area How about moving this section to Section 3 as a sub-section?

Author Reply:
Our preference is to keep the study area description in its own separate section as is common for many scientific manuscripts. However, we can move the study area section to the methods section if the reviewers and editors feel strongly about this.

6. Surface energy balance largely determines surface melt, which in turn dominates the runoffs. On this daily timescale and without analysis on refreezing, how does your study differ from those using surface melt instead of runoffs, especially when your conclusions are the same as those studies using surface melt?

Author Reply:
We will rewrite the paper to clarify that in agreement with previous work we find that the SEB budget explained the majority of the moulin discharge. However, we also find that evidence of catchment processes are influencing the stream discharge. Most important is probably our finding that the catchment modulates the delivery of surface melt to the moulin so that the timing of peak discharge changes over the season. As far as we know, our documentation of a changing time to peak over the season has not been shown with in-situ data for Greenland ice sheet streams prior to our work.

7. Line 272-273: "As the season progresses, the time to daily maximum discharge will reflect changes in network storage and transport efficiency." I like this sentence. It helps me understand why the timing of peak discharges is important.

Author Reply:
Thank you for the comment on this sentence.

8. Section 4.3: this rapid shift in timing is a new discovery. A solid explanation is warranted. How does the temperature change explain this shift?

Author Reply:
We appreciate the request for more explanation for the sudden shift in time of peak discharge around early August.

With respect to how a temperature shift explains the rapid shift in peak discharge timing: With the night-time air temperatures close to 1 °C, the skin temperatures could be below freezing. Thus, we suspect that meltwater delivery to the channels are slowed down due to freezing water. With below freezing temperatures, there is likely a change in the manning's n coefficient as frozen ice features pose an impedance to flow, in turn lowering the streams conveyance.

In the revised manuscript, we plan to devote more time to discuss these findings. Unfortunately, we lack many of the auxiliary data that could help us explain the change in the sudden peak. However, we will do a better job to discuss what those auxiliary data could be, i.e. precision stream temperature measurements and skin surface temperatures. We will also do a better job in explaining conceptual models for what could explain the change in peak timing. For example, below freezing surface temperatures could slow down flow, and a switch from channelized to overland flow after the peak melt event would also slow down the flow. Unfortunately, as mentioned, we don't have the observations to prove which conceptual model is dominating in our catchment, but we will discuss what observations are needed to figure it out.

We were recently able to recover a time series of water level observations in cryoconites holes in our catchment that we will add to the paper (see figure below). Our preliminary analysis of this data suggests a drop in the cryoconite water level that occurs around the same time as the change in timing in early August. While this data does not explain the abrupt change in timing that occurs in early august, it is indicative of a connection between the change in timing and reduced water storage in cryoconite holes.

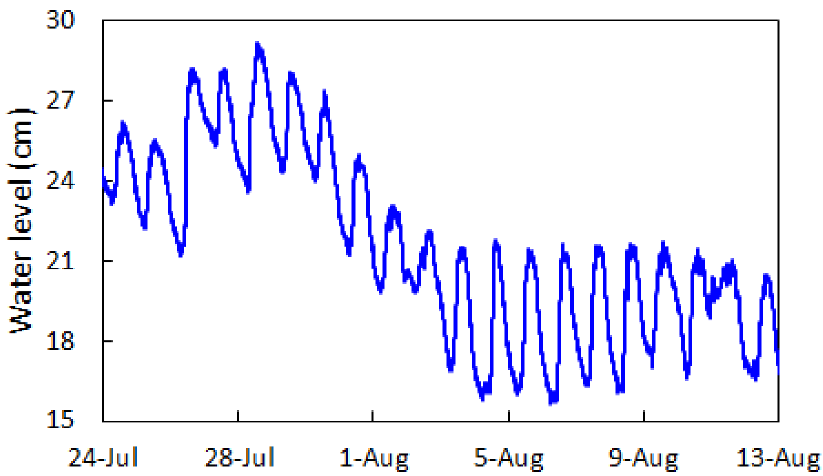

Fig: Water level in a cryoconite hole close to the discharge station, measured using a levelogger.

Revised version of Figure 6 will include cryoconite observations of water level and temperature

9. As for all significance tests, are the p values always = 0.00001 or <= 0.00001?

Author Reply:
Not all p values are less than or equal to 0.00001 (they are in the range of 0.00001-0.00011). Since they are extremely small, we will simplify the manuscript by just stating that they are ≤ 0.0001 throughout.

10. Line 295, what does it mean when the sum of exponent and the product of coefficients does not equal 1? Are they still valid? If the authors do not interpret their results, the readers may take it the wrong way.

Author Reply:
In theory the sum of exponents and the product of coefficients must equal 1, but in practice due to measurement error and when R^2<1.00, i.e., the power law does not perfectly describe the data, and we can expect deviations from 1. From the previous hydrological studies, we can conclude that if the sum of exponents and the product of coefficients are close to 1 the theory of hydraulic geometry holds. We will clarify this in the revised manuscript.

11. Line 24-27, I do not think this is a fair comparison considering the large differences in the temporal and spatial scales.

Author Reply:
We will rewrite this section and clarify that the transferability of our findings may also be affected by scale, i.e. our study catchment is on the smaller scale and also is placed at the lowest

part of the ablation zone.

12. Line 373, should the most accurate way be in-situ measurements? Or the next best, reanalysis?

Author Reply:
We will revise this sentence to clarify that regional climate models are the most widely used (instead of accurate) method to estimate surface runoff for the entire Greenland. At this time, it is not logistically possible to estimate all of Greenland runoff in situ methods.

13. Line 375, “lengthy”! “long-term”: Using “lengthy” suggests it is too long.

Author Reply:
As requested, we will replace “lengthy” with “long-term”