Response to anonymous referee #2

General Comments:

The authors use a suite of in-situ supraglacial streamflow observations to detail diurnal and seasonal variability in streamflow at the 660 catchment in southwest Greenland. Their analysis shows surface energy flux drivers of surface melt to shift in importance over the timeseries, and that the timing of daily maximum discharge evolves over the season. The authors give a solid introduction and discussion of the existing observations of supraglacial streamflow, and do a thorough job clearly describing the data sets they collected and how they've applied terrestrial hydrology methods to analyze observations of ice-sheet supraglacial hydrology. The figures are largely clear, with a few suggestions listed in the line-by-line comments below.

Prior to publication, however, the authors should work to improve the clarity of their discussion on the seasonal evolution in the timing of daily maximum discharge. In the abstract, a "changing effective catchment area" is listed as a main driver of changes in peak flow timing, but this driver is not fully communicated or supported in the discussion and conclusion sections. Mechanisms driving the direction of the change in lag between solar noon and the timing of daily maximum discharge (i.e., gradually decreasing from three to one hour over the season, and then increasing back to 3 hours at the end of the observation period) are not clearly discussed. The authors mention changes in the weathering crust may be important for both "expansion and contraction" (L396) of the effective catchment area, but give no directionality to this statement (Does the change to the weathering crust they envisage lead to a decrease or expansion of the effective catchment area? Would this result in a longer or shorter lag time?). A clearer communication of the physical changes to the weathering crust and the effects of these changes on the lag and effective catchment area is needed. If the authors can strengthen their discussion on lag evolution over the season, address the minor comments below, and tighten up the figures, the paper represents a solid effort in conducting and analyzing field observations of supraglacial streamflow, and will be of interest to TC readers.

In the revised manuscript, we will improve and clarify the discussion on the seasonal change in the timing of daily maximum discharge.
This will include a discussion about what auxiliary observations that would help explain the rapid shift in maximum daily discharge in early August. For example, observations of skin temperature and high precision stream temperature could reveal that the lowering of air temperature in early August also resulted in freezing streams. 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.

We will also add a new analysis to the manuscript that will provide some more context to the change in peak timing. New analysis includes a time series of water levels and temperature in a cryoconite hole (in the weathering crust). Our preliminary analysis suggests that the water level drops in the cryoconite hole over the span of ~20 days. The water level drop in the cryoconite hole shows a sudden drop in early August coinciding with the change in peak daily discharge timing. This suggests that the change in peak timing is linked to a reduction of surface water storage in cryoconite holes. We hypothesize that the drop in surface water storage and freezing overland flow melt due to colder temperatures could result in change in peak timing. While we lack the surface temperature observations to test this hypothesis, we will improve our writing and explain what observations are needed to test hypotheses about what is governing the change in peak timing.

Minor comments:

1. L13: Suggest referring to the 46 discharge measurements as “discrete measurements” throughout the manuscript, with “discrete measurements” being in contrast to “continuous” (5-minute) measurements.

Author reply:
Thank you for the suggestion, we agree that referring them to discrete measurements makes it clear. We will make this change in the revised manuscript.

2. L15: Suggest “of supraglacial discharge that captures both. . .”

Author reply:
We accept the suggestion and will add it into the revised manuscript.

3. L20: Include the baseline percentage contribution to the energy budget from longwave radiation, sensible heat flux, and latent heat flux, and not just the percentage increase of these contributions (as you have for shortwave radiation in the sentence prior). Otherwise, it is hard for the reader to understand what a percentage increase in these minor fluxes means in terms of the total energy flux.

Author reply:
We accept the suggestion and will include the baseline percentage contributions from longwave radiation, sensible heat flux, and latent heat flux in the revised manuscript.

4. L24: Suggest deleting “throughout the melt season”

Author reply:

We accept the suggestion and will delete the text from the revised manuscript.

5. L25: Suggest: "how widespread rapid shifts in the timing of peak discharge are across. ."

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

6. L33: Suggest remove citations to studies on Antarctic supraglacial hydrology (Bell et al., 2017; Kingslake et al., 2017), as these references do not address the subject of the clause: "surface melting also influences ice sheet basal properties".

Author reply:
We accept the suggestion and will remove both the citations in the revised manuscript.

7. L39: Suggest "melt season" instead of "melt season" throughout (e.g., L45).

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

8. L42: Suggest "often terminate in moulins, wherein meltwater moves through and beneath. . ."

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

9. L56: Did you mean to say "time lag decreases" here? As the network contracts, time lag decreases and discharge decreases. This would go with your findings in the abstract on effective catchment area decreasing resulting in a shorter lag.

Author reply:
After carefully re-reading the paper by Yang et al., 2018 we only find strong evidence for decreased stream network and decreased discharge amplitude. We will revise the sentence to make this clear.

10. L61: Suggest delete "thereby surface runoff"

Author reply:
We accept the suggestion and will delete the text from the revised manuscript.

11. L64: What about “Lesser drivers are. . .” instead of “Additional drivers are. . .”.

Author reply:
We accept the suggestion and will replace ‘additional drivers’ with ‘lesser drivers’.

12. L72: Two commas not needed around Gleason reference

Author reply:
We accept the suggestion and will remove the extra comma in the revised manuscript.

13. Figure 1: Plot the stream that presumably runs from the discharge station to the moulin. Also suggest coloring stream by stream order.

Author reply:
Thank you for the suggestion, we will plot the stream from discharge station to the moulin in the revised manuscript. We will also consider the suggestion about coloring stream by stream order.

14. L112: Suggest “46 discrete discharge measurements” instead of “occasional”.

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

15. Figure 2: Include approximate scale bars for all panels. An approximate vertical scale bar would improve reader understanding of Figure 2a. Remember that only a few privileged individuals have seen these streams in the field, and many will not have an innate sense of the vertical or horizontal scale.

Author reply:
We appreciate the suggestion and will include vertical and horizontal scale bars for each panel.

16. Figure 3: Keep all units in meters. All other figures are in meters. Clean up legends for the standard deviation bounds. Would “95% CI” be a clearer legend name here than “2 x stdev”? The data in Figure 3a is clipped by the top y-axis limit. Show all data. Maintain the same aspect ratio and axes limits across panels a and b. As presented with differing axes limits and aspect ratios, the panels cannot be compared by eye. Are these stream cross-sections for the wetted perimeter? If yes, say so. If not, where is the approximate water line (or range in water line)?

Author reply:

We appreciate and accept all the suggestions and will make appropriate changes in the revised manuscript. Yes, these cross-sections are for the wetted perimeter. We will mention this in the text and figure captions in the revised manuscript.

17. L141: Confusion. Should the reference to Figure 4 go here: "The rating curve (Fig. 4; Q=. . ., R2=. . .) was. . ." instead of after the second sentence in this paragraph? As written, the reference to Figure 4 for "hourly discharge data" does not make sense. Hourly discharge data is in Figure 5a, no?

Author reply:
Yes, it was a mistake. The reference for Figure 4 should go after the first sentence in the paragraph. Hourly discharge data is shown in Figure 5a. We will make this correction in the revised manuscript.

18. L143: Suggest include the "Therefore, . . ." sentence in the previous paragraph. Make the new paragraph begin at "Four uncertainty estimates. . ."

Author reply:
We accept the suggestion and will shift the sentence to the previous paragraph.

19. L144: Suggest "were calculated as percentage uncertainties (see. . ."

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

20. L144: Suggest "discrete" instead of "individual"

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

21. L144–145: Give the uncertainty variable namesâA˘TUME, URC, Xdm, and Uin(?)â ˘ A˘Tin˘ the first sentence where you introduce the four uncertainty estimates.

Author reply:
We accept the suggestion and will mention the variable names where we introduce the uncertainties.

22. L146: Are these 95% CI uncertainties?

Author reply:

Yes, these are 95% CI uncertainties (details explained in Appendix A). We will mention this in the text in the revised manuscript.

23. Figure 4: In legend, indicate whether the "observations of stage and discharge" plotted here are hourly or 5-minute discharge data. How many sigma are you plotting with URC? Suggest keep the 95% CI language from Figure 3.

Author reply:
We accept the suggestion and will indicate that the observations of stage are plotted from 5-min stage data and discharge from discrete discharge measurements. The shaded area plotting URC covers 2 sigma (it is mentioned in the text). We will make it clear in the figure caption as well in the revised manuscript. We will also include 95% CI information here in the caption.

24. L159: Suggest "we compared coincident depth profiles (Fig. 3) and velocity measurements"

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

25. L159: Are these velocity measurements ever shown? Show across flow profiles of stream velocity, which you "measured at each 0.2 m interval at 60% of the depth" alongside the stream cross-section depth profiles in Figure 3 or as a stand-alone new figure.

Author reply:
The primary purpose of the velocity is to calculate discharge. We choose not to visualize the across flow profiles of stream velocity because it does not directly add to the science questions we are investigating. We are happy to add it in case we are ignoring some process that the reviewer thinks we should consider, please let us know. However, the dataset includes detailed information about the velocity cross sections and can be used by anyone interested in the same.

26. L162Ân–3: Suggest giving 2 sigma values that will better align with the 95% CI given ˇ in L164.

Author reply:
We accept the suggestion and will add 2 sigma values for uncertainty due to incision in hourly and daily profiles.

27. L177: Suggest "discharge Q."

Author reply:

We accept the suggestion and will edit the text in the revised manuscript.

28. L184: State the elevation of KAN–L in comparison to the study site.

Author reply:
We accept the suggestion and will state the elevation of KAN-L station in the revised manuscript.

29. L185: State what variables are used from the KAN–L station.

Author reply:
We have only used energy components from KAN-L station in our analysis. We accept the suggestion and will state the variables used from the KAN-L station in the revised manuscript.

30. L190: Suggest: "to calculate surface energy balance components of net. . ."

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

31. L194: Give a citation for the Monin-Obukhov similarity theory.

Author reply:
We accept the suggestion and will add a citation for the Monin-Obukhov similarity theory in the revised manuscript.

32. L196: Reference Figure 1.

Author reply:
We accept the suggestion and will add the reference for Figure 1 in the revised manuscript.

33. L198: That's a lot of handheld GPS points!

Author reply:
Yes, we had set the GPS to record location for every second and walked along the catchment divide.

34. L199: A change in catchment size was not observed, but how does this align with the change in effective catchment area implicated in the abstract? Include a quantification of the time-varying effective catchment area.

Author reply:
Effective catchment area is the area that is connected through the stream network that efficiently transports meltwater generated in that area through the network and it varies with change in size of the stream network. As the stream network expands, the area from which it can transport the meltwater is increased and that is what we referred to as the effective catchment area. We plan to change the narrative from effective catchment area to size of the stream network (as the previous explanation leads to more confusion). We will explain this better in the revised manuscript to avoid confusion.

35. L200: State the uncertainty in meters.

Author reply:
We accept the suggestion and will add the uncertainty in meters in the revised manuscript.

36. L204: Are these repeat visits all during the melt season? As written, the visits could have occurred in the winter as well.

Author reply:
Yes, all these visits were during the melt season. We will clarify this in the revised manuscript.

37. L218–224: The sentence ordering in this section is confusing. Suggest stepping through the description of the timeseries linearly here.

Author reply:
We accept the suggestion and will rewrite the paragraph to avoid confusion in the timeseries of the events.

38. L219: Suggest “Between the second and third episodes, . . .”

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

39. L222: Suggest “melt episodes, which have large. . .”

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

40. L223: Suggest “amplitude from 0.64 m3s-1 on 21 July to 0.33 m3s-1 on 13 August.”

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

41. Figure 5: Make all of these panels the same width. Stack them vertically so the eye can travel vertically down the figure to compare the timeseries, just as you have done in Figure 6.

Author reply:
We accept the suggestion and will edit the figure to align the panels vertically in the revised manuscript.

42. L228: Does the mean daily discharge go all the way to zero? The lowest value in Figure 6a seems to be ~0.02 m3s-1. Suggest defining/describing what zero means when given as the lower bound here. Suggest keeping the same number of places past the decimal when reporting values in text.

Author reply:
We appreciate and accept the suggestion. Yes, the lower bound is not exactly zero in daily discharge. We will add the exact lower bound in daily discharge with the same number of digits past decimal as the higher bound.

43. Figure 6: Calculate total heat flux/energy from components in panel b, and then plot total heat flux/energy as the right y-axis on panel a.

Author reply:
The point of this figure is to show the radiation components and their variation over the melt season. We choose not to include the total heat flux because it does not add to our analysis and only adds too much information in the figure.

44. Figure 7: Note days that are not "clear sky" with vertical bars. State the proportion cloud cover cut off to designate a day as not being "clear sky".

Author reply:
As requested, we will add a shaded region in figure 7b that indicates times with large cloud cover and state a cloud cover threshold (e.g. 0.6).

45. Figure 8: Suggest "melt season".

Author reply:

We accept the suggestion and will edit the text in the revised manuscript.

46. L273: How different is the time lag on non clear-sky days?

Author reply:
As requested, we will add text to this paragraph to describe the differences between the time lag on clear-sky and cloudy days. The point we will make is that depending on the cloud cover and the time at which clouds disrupt the incoming solar radiation, we either had an earlier peak or a delayed peak in diurnal stream discharge over the day. For example, days with cloud cover for longer than 3-4 hours during the middle of the day (10:00 - 16:00 local time), have a peak discharge earlier in the day around noon to 13:00. On the other hand, days with shorter periods of cloud cover around mid-day, had peak discharge later in the day.

47. L278: Suggest "shifts back to initial season conditions of a 3 hour time lag in early August."

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

48. L282: Suggest "above the ice surface. . ."

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

49. Figure 9: Include the 2 to 3 clear-sky days between melt episodes 1 and 2 in mid-June on panel a to present the entire 62-day timeseries. Plot the time of daily maximum discharge for non clear-sky days with a different symbol in panel a. Would be interesting to see if the times on non clear-sky days are random, and this would further support your choice of investigating the seasonal evolution of lag only on clear-sky days. In the panel b legend, do you mean "Daily mean air temperature" ?

Author reply:
We will add an analysis of the time lag on cloud days to the text in this paragraph. This text will present these results: The R^2 for trend in peak timing in June and July for clear sky days is 0.79 and statistically significant ($p<0.01$). In contrast, the R^2 for trend in peak timing in June and July for all days, cloudy and clear sky, is only 0.15 and not statistically significant. We will add a figure that shows the peak timing of cloudy days to the supplemental material.

In the legend, the first time series is daily mean air temperature. We will clarify this in the revised manuscript.

50. L300. Give the 660 catchment size here, so the reader can better compare with the results from other studies that follow.

Author reply:
We accept the suggestion and will add the catchment size here in the revised manuscript.

51. L304: Does zero discharge mean a dry stream bed at portions of the day? Observations taken outside of the melt season? Suggest defining/describing what zero means when given as the lower bound in a range.

Author reply:
We will clarify that our range shows the minimum value and the maximum value reported by the authors of the paper. We also took a closer look at the paper by Marston et al. (1983) and found that the minimum value is only shown in a figure and it is very difficult to determine the exact minimum value. However, we can say that the number is close to zero (but not completely zero) and we will revise the text accordingly.

52. L307: Is this time local time? Suggest stating at the beginning of the paragraph that all times given will be given in the local time of the study sites.

Author reply:
We accept the suggestion and will state that all the times mentioned here are local time in the revised manuscript.

53. L309: Quantify and give how many times larger the Holmes (1955) catchment is compared to the 660 catchment.

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

54. L316: Suggest "In addition to diurnal variability, . . ."

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

55. Table 1: Suggest "660 Catchment (this study)" in the bottom row.

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

56. Table 1: Again, what do the zeros in discharge signify for the different studies? A dry stream bed for a portion of a day, or taking observations outside of the melt season?

Author reply:
We will explain in the table caption that all data presented in the table are from observations made during the melt season. In other words, the zero value represents a dry stream bed in the melt season.

57. L341: Suggest new paragraph at "For the 660 catchment,. . .", as you are now switching from comparing the total area of the catchment between studies, to the evolution of the catchment over time at 660.

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

58. L343: What does Mernild et al. (2006) attribute the change in lag to, and is this supported by your findings at catchment 660? Is it the change in effective catchment area you mention in the abstract? Add a few sentences on this here.

Author reply:
Mernild et al. (2006) attributed the change in lag to change in weathering crust structure. We also see such a change in weathering crust, possibly leading to change in lag time. However, they do not talk about change in the effective catchment area/size of stream network. We will make this concept of change in size of stream network clear in the revised manuscript and also write about the findings from Mernild et al. (2006), which we also concur.

59. L348: The last sentence shifts back to the effective catchment area (poor vs efficient network) as the reason for a shifting time of daily maximum discharge. But the sentence immediately prior discusses changes to the weathering crust. Suggest working through these points more carefully to clearly describe how a decrease in effective catchment area leads to shorter lag times, and how the weathering crust plays into this decrease in effective catchment area. Add citations for the L346 statements on how changes to the weathering crust under colder conditions would affect lag times. Does Yang et al. (2018) include weathering crust in their model? State this explicitly for readers who have not read Yang et al. (2018).

Author reply:

We accept all the suggestions and will make a clear discussion about the influence of changes in effective catchment area and weathering crust on the change in lag time. We will include citations as suggested in L346.
Yang et al. (2018) do not include weathering crust explicitly in their model, but consider flow patterns which mimic the meltwater flow through the weathering crust. We will explain this in the revised manuscript and make a clear discussion.

60. Table A2: Are all of these reported at 95% CI, or just the final row? Suggest keep everything at 95% CI and state that in the table caption.

Author reply:
The individual uncertainties are empirical estimations from the WMO (2010). Final uncertainty estimate from measurement error is calculated with 95% confidence. We will clarify this in the table caption.

61. L394: Split these ideas into two sentences: (1) a drop from 3 to 1 hours in lag due to a decrease in effective catchment area; and (2) back to 3 hours due to a sudden drop in air temperature that delays melt from leaving the weathering crust.

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

62. L396: “expansion and contraction” Doesn’t the increase in lag suggest this is an effective expansion of the stream network? A clearer communication of the physical changes to the weathering crust and the effects of these changes on the lag is needed.

Author reply:
When the stream network is expanded, the channel flow is reaching a larger area and can transport the meltwater from farther corners of the catchment. However, when the network did not cover channel flow in that area, meltwater generated flows through the weathering crust and overland, causing a slower routing to the nearest stream. Therefore, an efficient network is a longer/expanded stream network which can transport most of the melt generated at a faster rate than overland and subsurface flow. We will rewrite the discussion and conclusions to make this clear in the revised manuscript.

63. L399: Change “notice” to “observe”.

Author reply:
We accept the suggestion and will edit the text in the revised manuscript.

64. L434: “All uncertainties are expressed at the 95% confidence interval.” ← This is the sentence that would be very helpful to have early on in the main text Methods section. In general, a consistent level of reporting for the uncertainties is needed to allow the reader to easily compare uncertainties across measurements.

Author reply:
We appreciate and accept the suggestion and will add the text in the methods section in the revised manuscript.