

Black Text – original comment from reviewer (line #s correspond to previous draft)

Red Text – edits made to revised version of manuscript (line #s correspond to revised version of manuscript with tracked changes)

General comments:

I thank the authors for implementing my suggested changes and answering my queries. I still have a few comments and questions surrounding the runoff methodology and the new rate of runoff analysis.

Additionally, I still believe the writing could be improved further. I have made numerous suggestions below on where sentences could be rephrased to be clearer. The language used should also be more consistent. The authors interchangeably use varied vocabulary to describe the same thing (e.g., speed-ups vs ice acceleration, velocity transients; subglacial drainage system vs meltwater system, basal system, basal channels). I recommend going through the manuscript to make the writing clearer and to be more consistent as it will greatly help to improve the readability of the manuscript.

We thank reviewer for their detailed comments and have tried to address their concerns in our revised manuscript. Below we describe our changes in response to each of their individual comments.

Runoff methodology:

1. The authors state that they calculate runoff for late-season melt events by summing all grid cells in the catchment and then dividing by the number of cells to get the average runoff (not the total runoff for the catchment). However, as mentioned in my initial review, I'd like to clarify that the correct approach is to simply sum the grid cells of the whole catchment which will give the total runoff from that catchment entering the subglacial system below that catchment (assuming all water directly accesses the bed and there is no upstream subglacial influence – see later comments).

The reason, we do not elect to sum the total runoff of the catchment basin is because the short duration of the speed-up events (typically < 5 days) makes it unlikely that all melt across the 5,324 km² catchment basin is routed to North Lake on a timescale relevant to the observed speed-ups. This recommendation by the reviewer, however, did prompt us to change our methodology to be less generalized, and to use only the RACMO runoff points closest to North Lake rather the runoff average across the catchment basin. We revised our methodology to average the 6 closest RACMO grid cells to North Lake that are within the catchment basin. In doing so, we consider only the runoff within ~33 km of North Lake. This assumption is based on the velocity of subglacial flow estimated by prior studies in regions with similar conditions. For example, western Greenland lake drainage flood waters have been observed to flow at speeds ~0.3 m/sec (26 km/day) (Hoffman et., all 2011; Stevens et al., 2022). Further, subglacial water flow under ice of similar thickness (~1000 m) has been observed to travel at speeds of 0.2 m/sec (17 km/day) (Chandler et al., 2013). Thus, we estimate that during a single speed up event melt could flow distances of several 10s of km through the North Lake subglacial system, but is not likely to flow over distances required to pool runoff from the entire catchment. Further, we found that varying the number of grid cells used to estimate the average

runoff feeding the subglacial system did not significantly alter our runoff estimates or the observed correlations between speed up and runoff (Fig. S2).

We added a discussion of subglacial meltwater speeds to motivate this methodology on L225-231. Further, we added a supplemental figure (S2), which compares the 1-point, 6-point, and 44-point (original) average to a single point close to North Lake. The singular point and 6-point averages are very similar and are consistently larger than the 44-point average (which includes many higher elevation points), thus motivating this methodology revision. We stress however that none of the major trends discussed in the original manuscript have changed.

2. Multiple times in the manuscript the authors compare the magnitude of the late-season melt events to that of the early season lake drainage, whilst stating themselves that this is a generalised estimate that ignores any upstream influence (likely substantial). Given that the catchment-based runoff calculation is an underestimate (especially when using the average and not the total), I question whether a direct comparison between the two event types is justified. To improve the robustness of the runoff estimates, the authors could route RACMO using the hydropotential to the subglacial area affected by the North Lake drainages. Due to the large uncertainties in both RACMO and bed topography and the extra work required this isn't essential, but without a more thorough method to calculate the runoff, I recommend removing all comparisons in runoff magnitude between the lake drainage and the late season melt events.

We elected to revise our methodology as described above, given the short duration and location of our speed-up event analysis. We reiterate that we do not think a summation is justified as this would significantly overestimate the melt entering the North Lake subglacial system. Rather, we feel the average runoff from the local area provides a good estimate of the rate that water (mm w.e. per day) is being input into the subglacial system during the speed-up event. In the case of the lake drainages, the “effective runoff” (again calculated in mm w.e. per day) is well known from the volume of the lake basin, the lake drainage time, and the areal extent of the basal melt distribution (known from previous modeling of the local uplift). This allows us to make a direct comparison between the lake drainage volume and the RACMO melt estimates as both are in units of mm (thickness) per day. Although there is some uncertainty with this value, it is justified to say that the runoff magnitude from a lake drainage is much larger than the runoff associated with the late season melt events, especially given the rapid nature of the lake drainage (hours compared to days for the runoff events). These estimates for the lake drainages are defined as “effective runoff” and are denoted in purple (Figure 6) to distinguish these values from the RACMO estimates for the same events. As Figure 6 contains three known lake drainage events, quantifying the discrepancy between the RACMO runoff estimate and the melt stored in the lake is especially important to contextualize our results.

Rate of runoff analysis:

3. Thank you for adding the rate of runoff analysis to the manuscript. I do wonder if this analysis would be more suited to being in the results with the rest of your runoff analysis?

We agree that the methods of the rate of runoff analysis better fit in the methods section and this description has been moved to Section 2.2 (L247-252). We kept Fig. 8 and its subsequent discussion in Section 4.1 as we feel this is where it best aligns with the flow of the paper. The rate of runoff analysis was prompted by our results shown in Figures 6 and 7, which further nuanced our discussion on the controls of velocity response throughout the melt season.

4. L484-488: I'm a bit confused what point the authors are trying to make here. It's interesting that there is a positive correlation between ΔR and DOY, which is exactly why late season melt-induced speed-ups are of interest and why they trigger large speed-ups compared to melt events during peak melt season (i.e., because the rapid increase in runoff compared to preceding periods overwhelms the subglacial drainage system). Why does this add a complication?

Our word choice may have led to confusion. We do not think it is possible (given our methods) to completely deconvolve DOY from the various factors influencing speed-up (i.e., multiple variables such as the number of open moulins and the subglacial drainage system – presence of channels and/or cavities and the extent of their “connectedness” have all been shown to change over the course of the melt season). Further, we know that ΔR does not accurately reflect the melt stored in the lake basin and supplied to the bed during a lake drainage. Indeed, if we were to take into account the lake volume, the relationship between ΔR and DOY is substantially weaker. Thus, it seems in the early season the velocity response is predominantly predicted by the number of open moulins and the lack of efficient channels.

5. Additionally, I don't quite follow the authors comment about the rate of change of runoff in Section 4.1: “Thus, while we agree that changes in the rate of runoff may play a role in controlling the system response (particularly for runoff-driven events), we feel the temporal evolution of the melt system remains a key variable in the overall response of the ice sheet to meltwater forcing.”, The rate of runoff (melt, rainfall, lake drainages) is what predominately controls the temporal evolution of the drainage system (e.g., Schoof 2010; Hoffman et al. 2011, Bartholomew et al. 2011, etc). If you have high sustained melt going into the system, it will get efficient and respond less to melt or lake drainage events. This is why the lake drainages early in the melt season have large dynamic response. I recommend carefully rewriting this section to explain the points made in more detail, whilst also referring to the well-established concepts of subglacial drainage evolution in Greenland.

In reality, changes in runoff cannot fully explain the velocity response throughout the melt season, likely due to the fact that the subglacial landscape is influenced by other non-runoff related factors, such as the distribution of open moulins, basal topography, and the initial runoff needed to establish channels in the early melt season. We discuss these factors in the results/discussion as we do not find that rate of runoff is predominantly controlling subglacial efficiency at all points in the melt season. This can be seen in our Figure 8 regressions. Further, Figure 8 does not take into account the “effective runoff” associated with the lake drainage events. If we consider the additional melt entering the North Lake subglacial system during a lake drainage, the effective values of ΔR and ΔR_n , would be much larger. For example, if we consider the effective

runoff of the DOY 169 lake drainage (~110 mm/day on average), and divide/subtract it by the pre-event mean rate of runoff (26.6 mm/day), it results in a larger $\Delta R = 83.4$ and $\Delta R_n = 4.1$ compared to $\Delta R = 8.8$ and $\Delta R_n = 1.3$ using the RACMO runoff estimate of 35.4 mm/day. This complicates the relationships shown in Figure 8 and suggests that the lake drainage events actually have rather small dynamic responses compared to their effective runoff. As shown in the schematic in Figure 9, we argue this is due to the lack of open moulins in the early melt season and more localized introduction of meltwater to the bed, leading to the strong ice-bedrock coupling in adjacent regions. We have revised the text on L448-450 to clarify this point.

Section 4.2:

6. I believe this section still doesn't fit in with the rest of the main manuscript, and complicates the overall story. The influence of bed topography channeling an upstream lake drainage is very specific to this site. It does not fit in with the general inferences of the evolution of the subglacial drainage system through the use of trainset speed-up events presented in the rest of the manuscript. Moreover, it also highlights the flaw in the runoff estimates, that the subglacial drainage system beneath North Lake is well connected to upstream sources. I recommend removing this section to streamline the manuscript and to help present a clearer story.

We elect to keep Section 4.2 in the manuscript because this section attempts to explain a notable, intriguing outlier observed in our ice-velocity records. The reviewer suggests that we remove this section because it “complicates the overall story.” By contrast, we would argue that removing outliers—and not attempting to understand these outliers—is a disservice to the observations themselves, and the reality that there are multiple sources and pathways by which meltwater is introduced to the bed producing transient speed-up events captured by ice-sheet velocity records in the ablation zone.

Transient speed-up events captured by ice-velocity records in inland ice-sheet settings have multiple sources: local lake drainages, melt events, precipitation events, *and* propagating subglacial flood events from distal, up-subglacial-catchment lake drainages. The “DOY 180 event” we describe in Section 4.2 falls within this final category, and we would be short-sighted to approach our analysis of transient speed-up events without making the effort to attribute each speed-up event observed in the velocity records to their most likely source. In the first round of revision, we modified the manuscript better motivate this section and to provide a smoother transition from Section 4.1 into this section.

Specific comments:

7. Title: Seasonal subglacial drainage system evolution? The authors talk about surface drainage too, but I wonder as the focus is on the inferred evolution of the subglacial drainage system it is worth mentioning this in the title.

We elect to keep the title as is. That we are investigating the subglacial drainage system is indicated with “drainage-system evolution *beneath* the Greenland Ice Sheet”; adding “subglacial” to this title would be redundant.

8. L35: ...(GPS) observations of ice motion show that...
Replaced “Western Greenland Ice Sheet” with “ice motion” on L36
9. L36: Correct van de Wal et al. 2008 reference. I also recommend diversifying references for this bit (e.g., Andrews et al., 2014; Bartholomew et al., 2011)
Revised “del” to “de” on L37 Added references on L38.
10. L38: Delete “the details of”. Change “ice-sheet velocity” to “ice velocity”
Deleted and revised text on L38.
11. L39: Add “is often non-linear”
Added “often” on L39
12. L44: Suggest changing the end of this sentence to something similar to: “...varies throughout the melt season as subglacial drainage transitions from inefficient to efficient systems, modulating basal sliding. + references”
We elect to modify the suggested revision of this sentence on L49 to: “...and varies throughout the melt season (refs), as subglacial-drainage efficiency evolves and modulates basal sliding (refs).”
13. L46: Change “basal” to “ice”
Revised on L51
14. L48: Change “...how the ice sheet responds to...” to “how ice velocities respond to...”.
Change “ice-sheet sliding” to “basal sliding”.
Revised on L53-54
15. L51: Please add example references for supraglacial lake drainage studies
Added on L56-57
16. L52: Supraglacial lakes aren’t limited to the western margin, change to/or similar “In the ablation zone of the Greenland Ice Sheet...”
Edited L57
17. L56: Remove “glacial”. Change to “reduces friction between the ice and bedrock..”
Revised L61
18. L57: Delete “the” from “the lake drainage events...”. Delete “these”. Change to “...coincide with surface uplift driven by high water pressures in the subglacial drainage system”
Revised L63 accordingly
19. L59: I might be being pedantic here, but to me “ice sheet” refers to ice sheet wide processes, whereas lake drainages are local/regional. Perhaps say “ice”?
Revised to “ice” on L65
20. L62: The added definition is much appreciated here, perhaps change to saturated layer thickness at the ice-bed interface?
Added on L68
21. L68: Change to “surface uplift”
Revised on L74
22. L71: Change to “subglacial drainage efficiency”
Added “drainage” to L77
23. L75: Basal channels more commonly refer to channels under ice shelves. Suggest rephrasing sentence to/or similar: “Ice thickness also plays a role, with subglacial

channels under thick ice (define thickness) closing quickly (within hours to days) through ice creep...”

Revised L81-82 accordingly for the 1000-m ice thickness that is relevant to our study area and many other ice-sheet lake-drainage settings.

24. L78: Delete “These observations highlight the need for further study on the evolution of basal conditions.” Or change “basal conditions”

Deleted L84

25. L81: “ice-sheet speed up” suggests they are occurring over the whole ice sheet. Perhaps delete “ice-sheet”. And same for L82?

Deleted “ice sheet” on L86 and L87

26. L100: Suggest adding “localised lake drainage”. I’m still not entirely convinced you can confidently state that melt and rainfall events are smaller than lake drainage. With melt/rainfall events happening on much larger spatial scales, the increase in subglacial discharge for well-defined outlets will surely be larger than lake drainages. I suggest instead emphasizing the different spatial scales (local vs regional).

Added “localized” to L113

27. L101: Suggest changing to “transient ice velocity response to meltwater inputs...for annual ice motion”. I would suggest refraining/being more careful about the use of “ice-sheet velocities” throughout, with the studies and processes you discuss in this study are all regional/local scales.

Revised L114-115 as suggested

28. L103: Again, remove “ice-sheet”

Removed “sheet” on L116

29. L108-109: Suggest removing this line, as these two types of events operate on vastly different spatial scales.

We elect to keep this sentence. The spatial scale of late-season melt events and precipitation events are inherently of the same spatial scale because both events derive their spatial scales from the scale of atmospheric pressure systems moving over the ice sheet. The horizontal length scales of high- and low-pressure systems are tens-of-kilometers, to a couple hundred kilometers, in diameter. As such, both late-season melt events and precipitation events create runoff across tens-of-kilometer regions of the ice-sheet surface, and both can be considered as “catchment-wide” runoff events.

30. L106-120: Good justification for the study, and improved intro to the study site.

Thank you!

31. L113: Is the site 25 km away from the terminus of Jakobshavn Isbrae, or another glacier?

Revised to include that the study site is 25 km up-ice-flow from Saqqarliup sermia, which is a medium-sized tidewater outlet south of Sermeq Kujalleq (Jakobshavn-Isbrae).

32. L113: Change “ice-sheet” to “ice motion”

Revised on L127

33. L139: Suggest rewording 1-sigma errors to 1-standard deviation?

We elect to keep the wording as is. Reporting formal, 1-sigma errors is the standard error-reporting methodology and wording for position estimates from TRACK. This wording aligns with previous error reporting of these observations in Stevens et al. (2015, 2016, and 2024).

34. L223: Are you using the daily mean runoff or daily sum runoff from RACMO?

Mean – added to L219

35. L224: Add “ice surface catchment in which...”
Revised L220
36. L226: Shouldn’t this be the sum of all grid cells? How many grid cells is the catchment?
Revised L223 to state that we averaged across 6 grid cells. We averaged (instead of summed) because we did not think it was realistic that the drainage over the entirety of the basin was responsible for the motion recorded by the North Lake GPS sensors on a given day. Thus, we took an average, to estimate the amount of runoff at any given 11 km x 11 km grid cell (roughly the same scale as the area of the GPS sensors around North Lake) near North Lake as previously described above.
37. L228: Change to/or similar “This is a generalized estimate for the runoff that makes it to the bed directly below the lake, but neglects any upstream sources routed beneath North Lake through the subglacial drainage system”
Revised L223-231 to describe our methodology revision. We use the surrounding RACMO points that could realistically influence the transient speed-up observed at our study area (North Lake) to estimate runoff.
38. L235: Change “integrated” to “total”
Revised L238
39. L254: Again, I don’t think these claims can be made without more thorough methods.
See previous response (#2)
40. L237: Can you please add a reference for the timescale of North Lake drainage?
Added Das et al., 2008 and Stevens et al., 2015
41. L307: pre-melt season winter velocity? Perhaps for consistency just say “background winter velocity”
Revised to background on L310
42. L332: Change “Discussion section” to “Section 4.”
Revised to “Section 4.1” on L337
43. L332: The analysis on runoff variability will be more suited here, in the results.
See response to #3.
44. L336: Suggest changing “ice sheet response” to “ice velocity response”
Revised L342
45. L329: It will likely not make much difference, but I do think the effective lake drainage melt supply to the system should be your calculated effective runoff + RACMO runoff of the catchment for that day?
Yes, technically that is correct, but we feel it is important to distinguish between RACMO runoff estimates and volume of melt in the lake basin. Given the magnitude of the discrepancy, summing these two quantities does not change the nature of our results.
L389: Suggest rephrasing “the sliding behaviour of the Greenland Ice Sheet...” to/or similar “The relationship between ice velocities and surface melt are linked through the evolution of the subglacial drainage system.”
Revised on L366
46. L396: Change “basal hydrologic system” to “subglacial drainage system”
Revised on L379 and L381
47. L427: I don’t think you can confidently state it is smaller.
See previous response #2.
48. L434-435: I find this sentence confusing, please can it be rephrased?
Rephrased L408-409

49. L436: Change “subglacial meltwater system” to “subglacial drainage system”
Revised L409
50. L448: What is the maximum, mean or integrated flux? Do you mean runoff?
Revised to runoff on L428
51. L450: Change “speed-up response” to “magnitude of speed-up” or similar
Revised L429
52. L451: Delete “summer”
Deleted on L430
53. L452-457: This should be in the methods instead
Moved to methods Section 2.2
54. L445: This sentence adds confusion, with the “state” of the subglacial drainage system during the melt season being almost completely controlled by the runoff magnitude and variability... (e.g., Schoof, 2010; Hoffman et al., 2011 etc)
As discussed in comment #5, we discuss the subglacial drainage system as distinct from rate of runoff since our results do not show that the velocity response/subglacial efficiency is completely controlled by runoff magnitude and variability. The focus of this article is to examine the subglacial system through the dynamic velocity response corresponding to punctuated periods of enhanced melt or flood events. In a broad sense, we agree that runoff is correlated with ice velocities, which we state throughout our introduction and discussion. However, our results do not show a perfect correlation between the magnitude of runoff and velocity response, especially if we consider the large volume entering the system during a lake drainage event.
L450-482: I think this paragraph would be better placed in the results with the other runoff analysis, or possibly replacing the analysis of speed-ups compared to mean, max, etc runoff.
See response to #3. We do not elect to replace the analysis of speed-ups compared to the mean, max, and total event runoff as this highlights the discrepancy between the lake drainage effective runoff vs. RACMO runoff estimates.
55. L479: Be careful with the use of “melt events”, as I presume you mean peaks in runoff, which could also be caused by rainfall events?
Yes, we consider regional melt events and local flood events (associated with lake drainages). As described on L402-405, it is unlikely that the magnitude of precipitation would significantly impact our overall results.
56. L484: I suggest rewording to “The correlations between speed-up magnitude, DOY and the rate of change of runoff...”
Revised on L441
57. L485: Change “subglacial drainage state” to subglacial drainage efficiency
Revised on L443
58. L489: I would suggest rewording/removing. RACMO does not underestimate runoff from lake drainages – it doesn’t include them at all.
We state on the following L446-447 “RACMO runoff estimates do not account for the meltwater stored in the lake basin.” By omitting this line entirely, it does not bring attention to this important consideration to our rate of runoff analysis and results. Thus, the results of Fig S4 underestimate the runoff associated with the DOY 169/162 lake drainage events as plotted.

59. L496-497: Yes, but it is the preceding runoff characteristics that define the “state” of the subglacial drainage system. And if there were a large runoff event before the early-melt season lake drainage, the velocity response would also change.
See response to #5.
60. L508: Delete “glacial”
Deleted on L501
61. L509: Change “ice sheet” to ice
Revised L502
62. L536: Change “ice-sheet” to “ice”
Revised L524
63. L542: Confusing sentence, smaller amplitudes in what? Suggest rephrasing “horizontal sliding transients”, surely there are no velocity speed-up events before the lake drainage?
Revised to “but smaller horizontal sliding transients relative to the pre-speed-up event horizontal sliding” on L530
64. L543: remove “the” ...water filled cavities. And network instead of networks?
Revised L531
65. L545: Change “velocity transient” to “speed-up”
Revised L533
66. L547: Change to: early in the melt season.... Change “hydrologic system” to “subglacial drainage system”
Revised L535
67. L547: Change “the horizontal-velocity increases...” to “Increases in ice velocity associated with...”
Revised L535
68. L549: Suggest changing “meltwater conduits” to “connections”
Revised L537
69. L549: More drainages occur? Or is there simply just more active supraglacial hydrology (moulins etc).
Additional lake drainages occur throughout the melt season resulting in a larger number of cumulative lake drainages as the melt season progresses
70. L551: I think this sentence could do with being more nuanced and specifying that it increases frictional coupling in the distributed regions adjacent to efficient channels?
Added “adjacent to channels” on L552-553
71. L553: Timescale of closure is very dependent on ice thickness
Sentence revised to: “Finally, late in the melt season, decreased runoff causes channel closing by viscous creep on timescales of hours for the kilometer-scale ice thickness of our study region (Bartholomous et al., 2011), but potentially leaving a network of dewatered cavities.”
72. L553: Typo? “dewater cavities”
Correct, revised L555 to “dewatered cavities”.
73. L555: Change conduits to “connections” or just say moulins
Revised to moulins on L557
74. L631: Change “subglacial bed conditions” to subglacial drainage system
Revised L616

75. L632: Suggest removing “preliminary” considering the wealth of previous papers on this site and many other studies using GPS to infer subglacial drainage evolution in west Greenland.

Removed on L617

76. L645-648: Again, this doesn’t fit with the rest of the conclusion/ story on the manuscript
See response to #6, which describes why we elect to keep Section 4.2

77. L915 (Figure 6): Please check axis labels here and throughout (m year-1 should be m year-1). I think mm/day should also be mm w.e. day-1

Velocity units revised to “m year-1” in Figures 4, 5, and 10. Runoff units revised to “mm w.e. day-1” throughout.

78. Figure 1: Check axis labels throughout (m year-1 should be m year-1). How is the annual ice flow direction is indicated?

Annual ice-flow direction now included on the map-view panel a with an arrow. The y-axis labels for panels that show velocity estimates in this figure already include the correct units for velocity as “m year-1”.

79. Figure 4: Correct m year-1

Velocity units revised to “m year-1” in Figures 4, 5, and 10.