***Interactive comment on* "Brief Communication: Heterogenous thinning and subglacial lake activity observed on Thwaites Glacier, West Antarctica"**

Referee: Anonymous Referee #2
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We thank the reviewer for detailed comments with constructive criticism.

Our responses are marked as follows:

Reviewer Comment (blue italic)
Response (black)
New or changed text (red)

While the presence of active subglacial lake systems in Greenland and Antarctica has been known for decades, the impact of the filling and draining of the lakes on the ice flow is still not well understood. This paper provides a comprehensive investigation using remote sensing observations and continuous GNSS monitoring on the Thwaites and Haynes glaciers in Antarctica, in a region that is undergoing rapid changes in ice dynamics. The paper is well written and presents excellent observational data sets combined with modeling subglacial water routing and basal friction estimation. The study demonstrates an innovative use of remote sensing, including the generation of high temporal resolution records of vertical displacement from Sentinel observations and ice sheet elevation from radar altimetry. The combined interpretation of the observations and the modeling results suggests that ice acceleration is not or only weakly sensitive to subglacial drainage, and, thus, the authors conclude that while the 2012 speed-up of the Thwaites Glacier trunk occurred shortly after the 2013 drainage event, it was due to enhanced sub-ice-shelf melt. The study is worthy of publication and includes important results, but it still leaves some questions open. The authors lay out a convincing argument about the evolution of the subglacial conditions using reasonable assumptions, supported by previous work. However, the two GNSS stations provide only limited information for a basinscale interpretation. For example, it is not clear how sensitive the locations of UTHW and LTHW are for changes in subglacial hydrology or diffusion thinning originating from the grounding line. Showing UTHW on S Fig.3 would help in the interpretation.

We thank Reviewer 2 for raising the concern that localized GNSS coverage of Thwaites Glacier limits the extension of these observations to basin-scale understanding. We note that these two GNSS sites are the only two long-term sites that have been deployed on Thwaites Glacier and while their spatially coverage is inherently limited, they offer temporal resolution that is valuable for examining rapid processes, including lake drainages. Although serendipitous, the placement of the LTHW site is especially valuable for observing Thw_{124}. The UTHW site was selected to investigate large changes in modeled basal shear stress, but it is place along a central flowline, and thus is reasonably well-positioned to sample inland acceleration and thinning. We have added the position of the GNSS sites to Figure S3. In conjunction with this change and the additional text below, we also use monthly Eulerian observations of the glacier's speed to show that spatially distributed changes in glacier slip due to subglacial lake activity are small relative to the average velocity of the lakes before and after the 2017 drainage event (Fig S5). These observations complement the inversions before and after the lakes drain in 2017 and show no substantial difference in glacier speed due to lake drainage beyond the immediate vicinity of the lake (Fig. S4). These figures have been included in the supplement.

Line 132-135: Speed remained elevated at the LTHW site after Thw_{124} stopped filling coinciding with a 2-degree shift in ice-flow direction to the grid-north (clockwise), toward Thw_{124} (Fig. 3); however, this speed change is imperceptible in distributed velocity maps before and after Thw_{124} filled in 2017 (Fig. S5).

Supplement Figure 3: Average water flux assuming static hydropotential and basal melt rates from Joughin et al. (2009). Supplement movie shows weak sensitivity for water rerouting as the glacier thins and the lakes fill and drain. The cumulative water fluxes (km^3/yr) into lakes $Thw_{124,142,170}$ are printed with each lake. Black star and square indicate sites of LTHW and UTHW GNSS.

Also, due to its position on the boundary of Lake Thw_{124}, LTHW might be sensitive to complicated local processes that could even reduce the response to the drainage events.

We recognize that hydraulic flexure and viscoelastic response of ice near LTHW during and after lake drainage may contribute to complicated speed change we observe near the Thw_{124} lake margin (see lines 168-172). We note here that the response time of significant elastic deformation is faster than the 10 day speed up and slow down we observe at the LTHW GNSS in 2012. For comparison, the ephemeral subglacial lakes in Greenland that form following supraglacial lake drainage cause changes in ice velocity that equilibrate over the course of a single day (Stevens et al. 2015).

Also, there are two questions that the manuscript could have answered:

1. Smith et al., 2017 hypothesized that lake drainage events would occur in 20-80 years periods. Do the authors have an explanation of the observed much shorter timescale (~6 years).
The shorter timescale of lake filling and draining is certainly interesting. Because the timeseries is short and we do not know the absolute volume of the lakes, the water volume upstream of the lakes, or the connectivity of upstream water bodies to the Thwaites lakes, we do not feel we can say with confidence whether the lake drainages are fully inconsistent with the 20-80 year average period proposed by Smith et al. (2017). We also note that changes in lake storage capacity and lake drainage reoccurrence interval are also not always directly related, noted here for Thwaites but also documented on the Siple Coast (Siegfried et al., 2014; 2016), and indicate likelihood for non-constant recharge periods (see lines 168-172 of the revised manuscript).

Also, the range of elevation change is increasing in time (Fig. 3).
This statement is true for the largest Thwaites lake (Thw_{124}), which notably lies downstream of the other active Thwaites lakes. This observation is also consistent with subglacial lake activity observed along the Siple Coast (Siegfried et al., 2014; 2016). The apparent change in the storage capacity of Thw_{124}suggests that the lake volume and timing of lake drainage depends on the

dynamics of subglacial water flow between the lakes (initial effective pressure, conduit morphology, ice velocity, etc.) and hydraulic disconnection mechanisms in addition to the static hydropotential (lines 168-172 of the revised manuscript).

Could the shorter and more substantial variation indicate a rearrangement of the drainage system and a potential increase of its sensitivity to changing forcing?
In the movie supplement, we show a time series of the thinning observations (Movie SV1; doi:10.5446/44023) and changes in water routing affected by on-going thinning (Moive SV2; doi:10.5446/44035). The time-evolving Shreve (1972) hydropotential indicates that water routing is relatively insensitive to the progressive thinning that occurred over the time series of observations presented in this study. We do not observed sensitivity of hydraulic flowpaths to minor elevation changes (<15 m) that has been suggested to occur elsewhere in Antarctica (Wright et al., 2008). The Shreve hydropotential changes linearly with the overburden pressure, which decreases as Thwaites glacier continues to thin. Thus, although the effects of water routing are minimal, the ongoing thinning will likely change the storage capacity of the lakes and the characteristic fill-drain frequency, and we are doing work now to further understand these changes.

2. The authors conclude that the speed-up of Thwaites glacier following the 2013 drainage event was due to increasing sub-ice melt rather than the subglacial lake drainage events. Does it mean that the two types of events (acceleration and drainage) not connected? Or could the drainage events be caused by slight changes in velocity/subglacial routing as the glacier started to speed up and thin?
The acceleration and drainage cannot conclusively be linked; however, the acceleration due to the mechanics of lake drainage from the 2012-2013 GNSS record appear to be larger than the background rate of acceleration we attribute to thinning near the grounding line. This suggests that the dynamics of the lake filling and draining may locally and temporally supersede the effects of acceleration due to thinning upon initiation of lake filling or draining. We state this in lines 175-177 and also recognize that these fluctuations are of insufficient magnitude and duration to affect long-term trends.

Lines 36-37: I suggest to show Backer Island and Howard Nunatak on Fig. 1. I assume that the distances are relative to one of the GNSS receivers – which one?
We have modified Figure 1 to include Backer Island and Howard Nunatak. We have included the distance from Howard Nunatak to both sites as the Howard Nunatak reference station was used to kinematically process the on-ice GNSS positions posted in all of the figures and described in the text. See further changes below.

Line 39: Include reference for Savitzky-Golay filtered averages
The reference for the Savitzky-Golay filter was considered for this text; however, we are only allowed 20 citations. We request that we are allowed more citations and include the Svitzy-Golay citation as follows.

Line 39-40: We then constructed velocity time series from these geodetic solutions using 3-day Savitzky-Golay filtered moving averages (Press et al. 2007).

Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery (2007), Numerical Recipes, 3rd ed., Cambridge Univ. Press, Cambridge, U. K.

Line 39-40: What is the time period for the Eulerian speed? Is it a mean velocity for a longer period or derived from a single SAR image pair?
The time period of the Eulerian speed is a mean velocity product from 2015-2019, but excludes velocity maps sampled when significant vertical velocity change over the lakes affects the assumptions for distributed horizontal velocity. This explanation is now included in lines 40-41 and the Figure 1 text.

Line 45: I assume that the component of motion in LOS direction was estimated by InSAR processing. Please include a reference
The component of motion in LOS direction was estimated from SAR processing. We have added citation in lines 46-47 .

Line 46-47: We also computed the component of motion in the satellite line-of-sight (LOS) direction (Gray et al., 2005; Friedl et al., 2020).

Line 54: Add the word "solid" before vertical bars to distinguish from the dashed vertical bars
Sentence has been modified as suggested.

Line 53-56: To more tightly constrain the timing of the drainage events, we spatially interpolated the time series of Sentinel-1 derived Vz to fill gaps in coverage and integrated the result during a period of filling/draining (see solid vertical bars in Fig. 2c) to produce estimates of net uplift and subsidence shown in Figure 2a.

Lines 65-66: Include explanation for E (expected value)
The expected elevation statistics are defined in Smith et al. (2017); however, we agree that these statistics should be described again to provide context for readers without consulting another paper.

Line 67-70: The elevation statistics, $E\left(\frac{\partial^2 z_0}{\partial x^2}\right)$, $E\left(\frac{\partial^3 z_0}{\partial x^2 \partial t}\right)$, and $E\left(\frac{\partial^2 z_0}{\partial t^2}\right)$, represent expected values for spatial and temporal derivatives of the reference elevation model, z_0, and the time dependent height-change field, z.

Line 65-67: This sentence is confusing. What is the "respectively" refer to?
This sentence aimed to state the elevation statistics and compare these values with those previously used to compute elevation change on Thwaites Glacier in Smith et al. (2017). The word respectively is used to link the factor change in expected value to the associated elevation statistic ($E\left(\frac{\partial^2 z_0}{\partial x^2}\right)$ was changed by a factor of 5 and $E\left(\frac{\partial^3 z_0}{\partial x^2 \partial t}\right)$ was changed by a factor of 10 relative to Smith et al. (2017). We have attempted to reword for clarity.

Line 68-71: The values chosen for this study are $E\left(\frac{\partial^2 z_0}{\partial x^2}\right) = 6.7 \times 10^{-8}\, m^{-2}$, $E\left(\frac{\partial^3 z_0}{\partial x^2 \partial t}\right) = 6 \times 10^{-9}\ \mathrm{m^{-2}yr^{-1}}$, and $E\left(\frac{\partial^2 z_0}{\partial t^2}\right) = 1.0\mathrm{myr^{-2}}$, and tighten the spatial variations in the least square's elevation-change time series, $E\left(\frac{\partial^2 z_0}{\partial x^2}\right)$, $\mathrm{E}\left(\frac{\partial^3 z_0}{\partial x^2 \partial t}\right)$ compared to the original Smith et al. (2017) paper by factors of 5 and 10, respectively.

Lines 83-84: The western Thwaites tributary and Haynes Glacier Lakes appears to be switched, according to the text, the Thwaites tributary (WT) has a large drainage event, while Fig. S2 shows the larger drainage for the Haynes Glacier lakes.
We appreciate this correction. See changes to Figure S2.

Lines 99-100: It is not clear what different average fill rates refer to. For example, ~0.16 km3/yr appear to refer to the subglacial routing (Fig. S3), but the next sentence mentions the same estimate with a different value.
We have changed the second and third sentence in this paragraph to more accurately convey the origin of the volume change rates.

Line 108-111: From the altimetric observations of the Thw_{170} fill cycle, the average fill rate is ~0.16km^3/yr (Fig. S3). This agrees with the fill rate (~0.14km^3/yr) we calculate by routing inferred basal meltwater production (Joughin et al., 2009) down the glaciostatic hydropotential gradient (Shreve, 1972) into Thw_{170}, but requires inflow of all melt water produced upstream into the Thw_{170} lake basin (Fig. S3).

Line 135: LTHW is not shown in Fig. S3.
We thank referee 2 for noticing this omission. LTHW is now included.

Figures:
The names of the lakes should be shown in the same way everywhere. Currently, both THW124 and Thw124, etc. are used. Figure 1 caption: include the date (period) of the MODIS mosaic and the SAR velocity
We thank referee 2 for catching the inconsistent labeling. The lakes are now marked consistently throughout the text and figures. We have also added the dates for the SAR averaged velocity data and a citation for the MODIS mosaic (Haran et al., 2014). The Figure 1 caption now reads:

Figure 1. Location map of Thwaites Glacier and subglacial Thwaites lakes. (A) Average ice speed between 2015-2019 omitting period when lakes were active (colour) plotted over Moderate Resolution Imaging Spectroradiometer (MODIS) image mosaic (Haran et al., 2014). Thwaites Glacier, Thwaites Lake 124 (Thw_{124}) Thwaites Lake 142 (Thw_{142}), Thwaites Lake 170 (Thw_{170}), Haynes Glacier (HG) lake, Western Thwaites (WT) lake, and GNSS sites (LTHW and UTHW) are labelled. Thwaites lakes are named by their approximate distance from the grounding line. (B) LTHW and (C) UTHW GNSS position plotted over time (colour) with contoured mean velocity between 2015-2019.

Figure 2 caption: include projection – I assume it is EPSG 3031. Including a verbal description of the different symbols would make it easier to understand the figure, e.g., "from SAR LOS (colored dots, left abscissa or axis, locations marked in panels A and C3 B).

The projection is EPSG:3031 (polar stereographic centered at the South Pole, with latitude of true scale at 71ºS and the central meridian is the prime meridian). We have changed the figure 2 caption to the text below.

Figure 2. Surface elevation-change time series over the Thwaites Glacier lakes showing the 2017 drainage cascade from (A) vertical displacement computed from integrated vertical displacement rates (Vz) from Sentinel-1 SAR data and (B) swath-processed radar altimetry in a polar stereographic projection (EPSG:3031). Water volume (km^3) associated with observed vertical displacement is labelled for each lake. (C) Time series of uplift rates (Vz) from SAR LOS results (coloured dots, left abscissa; locations marked in panels A and B and horizontal speed from GNSS observations (right abscissa). Solid lines represent period over which SAR vertical displacements (Vz) were integrated to produce the vertical displacements shown in panel A. Dotted lines represent the quarters of gridded CryoSat-2 data differenced to create panel B.

Figure 3 caption: again, description of the symbols in the caption would be helpful, especially for the symbol showing the angle, e.g., "Also plotted the LTHW GNSS station direction change (purple dots)." Should include a reference to Fig. 1 for finding the locations and abbreviations. Finally, which direction is the direction given? Clockwise or counterclockwise?

The direction is clockwise, so shifts to the north relative to the westward flow direction. See additions to figure caption below.

Figure 3. Time series of GNSS velocity anomalies at UTHW and LTHW corrected for advection using the Eulerian velocity products and CryoSat-2 lake elevation change averaged over each lake area . See *Fig. 1* for site locations and abbreviations. Also plotted are LTHW GNSS clockwise direction change relative to 2010 flow direction (purple). The dark grey shaded periods indicate intervals when the LTHW GNSS accelerated significantly (99% confidence) while the light grey periods indicate when the lakes drain. When the largest lake fills in 2017, the LTHW GNSS closest to the lake accelerates and flows towards the lake.

References

Stevens, L., Behn, M., McGuire, J. *et al.* Greenland supraglacial lake drainages triggered by hydrologically induced basal slip. *Nature* 522, 73–76 (2015). https://doi.org/10.1038/nature14480