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

Referee: Anonymous Referee #1
Received and published: 18 May 2020

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)

General comments: This paper describes the behaviour of subglacial lakes in the Thwaites Glacier region. It describes an extension to an existing dataset with valuable new observations. It is well-suited for a 'brief communication' as it is timely and of relevance to ongoing research in this area. The authors use the new data to support the conclusion that subglacial lakes have a small effect on overall ice flow and conclude that their fill-drain cycles can be largely ignored when interpreting long-term trends due to the negligible effect on basal friction. The results are concisely presented.

Specific comments: Both the filling and draining of lakes have a small effect on the instantaneous velocity, but it seems that the long-term effect on the rate of acceleration is more ambiguous. There is definitely a change in acceleration between 2010-12 and 2014-15. Is the authors' opinion that this is as a result of the lake drainage or driven by change elsewhere on the glacier?

Referee 1 suggests that the filling and draining of lakes has a more ambiguous effect on the rate of long-term acceleration across Thwaites Glacier than we conclude in the paper. Negative acceleration in ice motion near Thw_{124} across the GNSS data gap between 2013-2014 followed by the faster rate of acceleration when GNSS begin telemetering in 2015 is the combined signal of lake activity and ongoing thinning. Acceleration that would accompany progressive thinning over this period is convolved with changes in the stress state due to lake dynamics and the subglacial hydrology system and cannot easily be disentangled without sub-annual distributed velocity information, which are not available for this time period (2010-2014). We present distributed velocity data during the second lake drainage event in this manuscript. Before and after the upper Thwaites lakes drained, filling the largest Thwaites lake, the velocity of the ice in the vicinity of the lakes does not discernably change (Fig. S3). We note that this drainage cycle is ongoing and that Thw_{124} has not yet drained since filling in 2017. Although repeated active lake drainage events are somewhat similar elsewhere where observations do exist (Siegfried et al., 2014, 2016), they are not identical. As we have no distributed velocity data that spans the full upper Thwaites lake drainage sequence, we prefer not to speculate on velocity expression of the first series of lake drainages besides noting that it is due to both progressive thinning and subglacial lake activity. These thoughts are more concisely presented in lines 169-175 of the revised manuscript.

The lack of acceleration across the GNSS data gap in 2013-2014 followed by a faster rate of acceleration afterwards requires additional explanation.
The lack of acceleration across the GNSS data gap could be the result of many different speed-up and slow down scenarios driven by combined lake activity, localized viscoelastic ice response to the drainage, and basin-wide acceleration. As we stated above, additional sub-annual distributed velocity data are not available for this time period to evaluate hypothetical scenarios. Due to the GNSS receiver power failure, we only know the average change in speed over this period and the acceleration after the GNSS began telemetering again. We do have distributed velocity data from the second lake drain-fill cycle in 2017, which indicates that the resistance field in the boundary of the lake does not discernably change before and after the lakes drain. This observation later in the timeseries coupled with the observed speedup near the grounding zone in 2013-2014 measured with feature tracked remote sensing imagery (Fig. S6 from Smith et al., 2017) suggests that the acceleration after 2013-2014 may be the catchment interior responding to thinning initiated at the grounding line in response to increasing basal-melt rates driven by ocean warming in the Amundsen Sea (Christianson et al., 2016); however, without distributed velocity data at sub-annual temporal resolution over the lake during this period, it would be conjectural to attribute the stagnation and acceleration to one series of mechanisms. We summarize these thoughts in lines 168-172 of the revised manuscript.

These new observations suggest that the observed speed-up at the grounding zone of the main trunk of Thwaites Glacier following the 2013 drainage (Smith et al., 2017) was associated with warming ocean conditions following anomalous Amundsen Sea wide ocean cooling from 2012-2013 (Christianson et al., 2016). These warm ocean conditions likely enhanced sub-ice-shelf melt and led to increased ungrounding and acceleration.

Contrary to the main conclusion, this overall long-lasting drop of ~5% in velocity relative to the 2010-2012 trend may still have some importance in decadal trends. Despite these minor details the overall conclusions of the paper appear reasonable.
When considering the impact of lake activity on ice motion there are two process timescales: (1) a fast response that includes the viscoelastic response of the ice-sheet and (2) a slow viscous response toward a new equilibrium. The fast response can only be measured with GNSS, while the slow response changes the equilibrium geometry and speed, which we measure with satellite remote sensing. Lake activity can affect both of these modes of ice sheet response by flexing the ice sheet, during rapid lake filling and draining, and dewatering the bed, which can change the local basal resistance on the timescale of lake filling and draining (years to decades, Smith et al., 2017). Furthermore, the effects of lake activity on elevation and velocity change appear to be quite local (see Fig. S3). During the 2013-2014 data gap, the acceleration at the LTHW station (at the boundary of the draining Thw_{124} lake) changed from ~3m/yr^2 (average acceleration before the drainage event) to ~0m/yr^2, but this fluctuation represents less than 3% of the total velocity signal and is much smaller than the velocity variability driven by changes near the grounding line (Miles et al., 2020). Due to the lack of distributed highly temporally resolved velocity data during the 2012-2013 drainage period, we cannot determine the spatial extent of these changes,

limiting our ability to attribute speed changes to local (lake drainage) or broader (basin-wide thinning) processes. The fact that the GNSS located at the boundary of Thw_{124} was only minorly affected by change in slip (~1% speed increase) when the lake filled in 2017 suggests that ice flexure and changes in the sliding speed due to lake fill and drain cycles have a spatially limited affect on ice motion. The snap-shot inversions over the lakes before and after the system drained in 2017 are consistent with this hypothesis (Fig. S5). The shear stress inside the lake boundaries does not change significantly, indicating that shear stress is low inside the lake area regardless of lake level (inversions were done before and after the 2017 Thwaites lakes drainage event). Therefore, we conclude that the lakes have only minor and localized effects on ice dynamics. These effects are far too limited in area and magnitude to affect basin wide velocity trends. We present these thoughts more compactly in lines 168-172 of the revised manuscript.

Technical comments:
Fig 1: needs a/b labels
Figure 1 has been modified to include labels A, B, and the addition of a C subpanel to distinguish the LTHW and UTHW GNSS sites. We thank the reviewer for catching this omission. See modified figure text below. Also, note change to Thwaites Lake identifier Thw_{124}, which is in lower case to be consistent with literature (Smith et al., 2017) and references throughout the text. We have also added the dates for the SAR average velocity field and a citation for the MODIS mosaic.

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.

Fig 2: I would swap the y-axes for ease of reading, given the temporal distribution of the data.
We have kept the axes as they were first plotted to emphasize the vertical velocity change we measure in SAR LOS data, which was plotted in the primary axis position with the observed speed change plotted in the twin axis position. This also matches the axes plotted in the supplement for the Haynes Glacier lakes. We think this allows easier synthesis with the spatial extent of the vertical velocity change plotted in panels A and B of this figure for the time periods shown in panel C. We have changed the figure 2 text to better link the subplots and aid reader interpretation (see changes 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.

Line 85: does this refer to the filling rate or the draining rate?
Line 85 refers to the filling rate. See sentence (line 89 in revised manuscript) restructured for clarity below.

Line 89: The western Thwaites tributary lake (WT), however, fills significantly at a rate of 0.1km^3/yr after draining in 2014.

Line 95: what is the evidence that it is driven from upstream and not downstream?
The differences in static hydropotential between the lakes is too large for the connection to be driven by the downstream lakes. See Supplement Figure S4.

Line 100: reword the sentence "This roughly..." for clarity
The sentence starting in line 100 has been changed to read:

Lines 105-107: This agrees with the fill rate (~0.14km^3/yr) we calculate by routing basal meltwater production (Joughin et al., 2009) down the Shreve 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: reword the sentence "Enhanced lubrication..." for clarity
Line 135 has been changed to read:

Line 142-145: Enhanced lubrication outside the low-drag Thw_{124} basin as the lake begins to drain likely increases local slip and drives the subtle change in ice-flow direction that we observe in the austral winter of 2012 before the peak drainage in 2013, when flow direction shifts back to the mean flow direction between 2010-2012.

Supplement: I assume the figure at the bottom of page 5 is the panelled image referred to in S4 (now S5)? Perhaps consider renaming it to S5.
The Supplement figure S5 has been modified into two panels. The primary panel has been labeled A, and the figure showing the difference in the inferred friction proxy has been labeled S5 B. See change in description below.

Supplement Figure 4: Static inversion for basal resistance field for 2017 catchment geometry (A) before the Haynes Glacier and Thwaites Glacier drainage events and (B) difference in inferred basal resistance between two static inversions from 2017 and 2018 (before and after the 2017 drainage cascade) for $Thw_{124,142,170}$.

References

Miles, B., Stokes, C., Jenkins, A., Jordan, J., Jamieson, S., & Gudmundsson, G. (2020). Intermittent structural weakening and acceleration of the Thwaites Glacier Tongue between 2000 and 2018. Journal of Glaciology, 66(257), 485-495. doi:10.1017/jog.2020.20