Reviewer 2

Review of 'Ice speed of a Greenlandic tidewater glacier modulated by tide, melt, and rain' by Sugiyama et al., for The Cryosphere

Summary

This manuscript investigates the short-term drivers of speed variability at Bowdoin Glacier, a medium sized outlet glacier in Greenland, using three deployed GPS receivers during six summers from 2013-2019. 3D ice motion is compared to tidal fluctuations and AWS-recorded near-surface air temperature and precipitation. Units were deployed at approximately the same location each year and oriented along flow with one unit nearest the terminus, and the third ~4 km inland. The study finds that glacier speeds responded both diurnally (melt-driven signal) and semi-diurnally (tide-modulated), though the later forcing decayed in influence with increasing distances from the front. Rain-driven acceleration was also detected in some years, though inconsistently across years, which is attributed to the subglacial drainage system evolution and dependency on the state of the subglacial system when precipitation events occur. Tidal influence was strongest near the front, and most pronounced once the terminus is believed to be at or near flotation heights. Most interestingly, this study shows that the 2 inland GPS receivers record uplift during periods (up to multi-day) of acceleration on the order of several centimeters, which is linked to the physical separation of the glacier from the bed as pressurized subglacial drainage systems form.

The manuscript is well written and arranged in a comprehensive and logical structure, with appropriate figures that complement the main results in the text. The study presents important results for understanding drivers and response times of dynamic outlet glaciers and evolving subglacial systems and offers valuable in situ observations that capture processes that occur at higher frequency than can be captured by most remote sensing studies. This manuscript is therefore nearly suitable for publication in TC in its current form, but I find there to be two topics that warrant further analysis/discussion in the main text, mainly: context on the position and phase of the terminus throughout the study period and (2) more figures that describe how key variables (such as lag time and coefficients of temp/speed relationships) vary between years and any trends that were observed. These themes are discussed below in the 'Main', followed by minor comments and requests for clarification.

Thank you very much for reviewing our manuscript. Below (in red), we address the review comments and explain how we revise the manuscript.

Main

Terminus change: Some general description of Bowdoin's terminus change are provided in the background, but it would be beneficial to include more information on terminus change during the study period, especially because variations in distance-to-front is found to be an important component on varying responses to tidal impacts between sites 1, 2 and 3. Similarly to the phase of tidal change, the phase of terminus change (whether advancing of retreating), and distance from the nearest GPS receiver (unit 1) each year, and the range in that distance over the seasonal study window, are all important variables that may lend more context to various signals detected during the 2013-2019 period. While I believe the terminus remained relatively stable after 2013 as compared to the large retreat in the preceding years, the interannual variability in when advance/retreat occurs (if any) would still be important to address in this manuscript.

To address the reviewer's concern, we analyzed the variation of the front position over the study years (2013–2019) (Figure 1a). The front position data were obtained from Zhang et al. (2023) and processed using the box method provided by Lea (2018).

From 2013 to 2019, the glacier front showed seasonal variations with an amplitude of 100–200 m (Figure 1a). Despite the seasonal position change, the glacier front was situated at similar locations every summer, which were distributed within ~100 m (Figure 1b). During each of the summer measurement periods, the range of the frontal variation was relatively small (typically smaller than 50 m).

Our analysis indicates the change in the glacier position during the measurements was not large as compared to the distance to the GPS sites from the front (~0.5, 2.5 and 4 km). As far as we have investigated the data, there is no significant influence of the front position or its change on the ice speed variations. Further, primary influence of meltwater production on the seasonal ice speed variations was reported in Bowdoin Glacier, whereas no clear relationship was found between the speed change and the front position (Sakakibara and Sugiyama, 2020). Therefore, we show the front position data as a supplemental material, but do not discuss details on its influence on the ice speed variations.

Lea, J. M.: The Google Earth Engine Digitisation Tool (GEEDiT) and the Margin change Quantification Tool (MaQiT) – simple tools for the rapid mapping and quantification of changing Earth surface margins, Earth Surf. Dynam., 6, 551–561, https://doi.org/10.5194/esurf-6-551-2018, 2018

Sakakibara D., and Sugiyama S.: Seasonal ice-speed variations in 10 marine-terminating

outlet glaciers along the coast of Prudhoe Land, northwestern Greenland. J. Glaciol., 66(255), 25–34. https://doi.org/10.1017/jog.2019.81, 2020

Zhang, E., Catania, G., and Trugman, D. T.: AutoTerm: an automated pipeline for glacier terminus extraction using machine learning and a “big data” repository of Greenland glacier termini, The Cryosphere, 17, 3485–3503, https://doi.org/10.5194/tc-17-3485-2023, 2023.

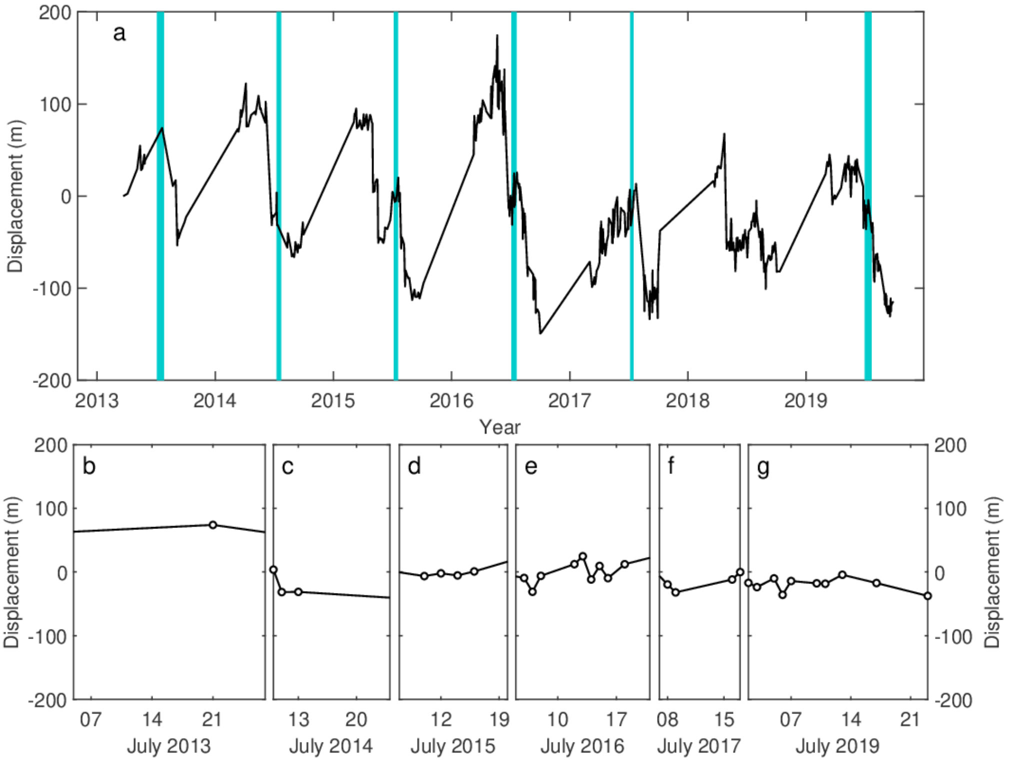


Figure 1 (a) Frontal displacement of Bowdoin Glacier relative to the position in March 2013. The shades indicate the GPS measurement periods. (b–g) Same as (a) for the measurement periods in 2013–2017 and 2019.

Interannual changes in key variables:

A main strength of this manuscript over previously published studies at this glacier is the extended 2013-2019 study period, which enables the authors to investigate trends and interannual variability in key characteristics of ice flow. While the ‘stacking” approach across multiple years was necessary to conduct the fast fourier transform and identify the dominant frequency components, multiyear mean values (such as shown in Figure 4) exclude potentially informative information on how seasonality and characteristics of low have evolved over time. For example, the temperature-max speed lag time of 2 hours was only provided for GPS3, and using a mean result from stacked daily values. It would be useful to understand how this lag compared across years at GPS3, or even compared to lag time at GPS2. Another recommendation on this theme would be to provide corresponding text in the main manuscript that describes the relationships seen in the scatter plots (which include all years superimposed). The plots by themselves are not super informative, and difficult to discern how correlations vary (or remain consistent) across years.

Figure 4 was obtained by subtracting a general trend, stacking data in each year, and taking a mean of the results from six years (Figure S2). As it is seen in Figure S2m, the discussion of the lag between ice speed and temperature peaks is only possible after stacking and taking a mean of available data. It is not possible to discuss seasonal or year-to-year variations based on Figure S2m.

We analyzed the data set from GPS3 because it is not affected by the tide. Because ice motion at GPS2 is influenced by tide (Figure 3), ice speed variations should be discussed with tidal variations as well as temperature.

Further discussion of the scatter plots of ice speed v.s. temperature (Figure 5g–i) are given in Line 278–285. Deviations from the general relationship in 2013 and 2016 are explained by speed-up events. Year-to-year variations are attributed to the efficiency of subglacial drainage efficiency. More detailed discussion for each year is not possible based on our data.

We thank the suggestion and encouragement of the reviewer. However, our six-year data set is just enough for the discussion presented in the manuscript, but not sufficient for detailed analysis of seasonal or year-to-year variations.

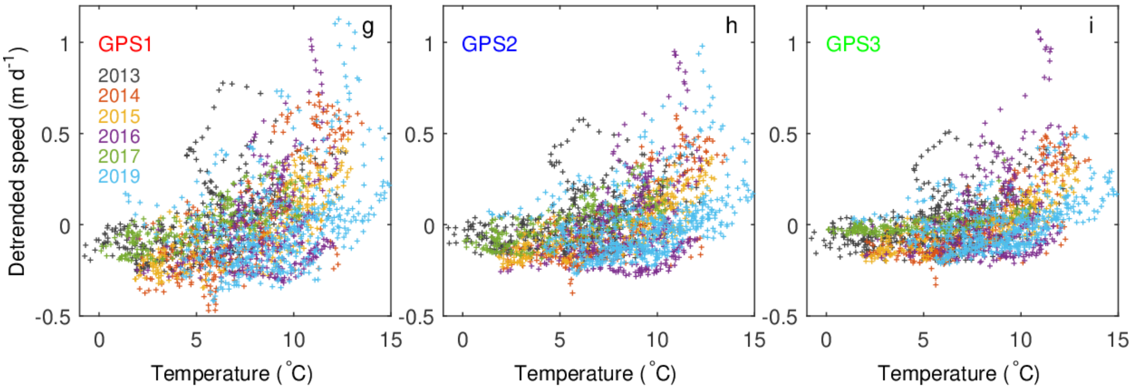
Minor

Request for more clarity: Were 2013, 2014 and 2017 the only years where precipitation was recorded during the study period?

The automatic weather station was operated during the field campaigns as described in Line 139. Precipitation was detected in 2013, 2014, 2016, 2017 and 2018 as shown in Figure 2a-f. I am not sure why the reviewer misunderstood.

Scatter-plots (for example, in figure 9): Consider using a colormap that avoids very similar colors. It is difficult to discern the years shown in light blue and darker blue (2013 and 2019).

We will change the dark blue (2013 data) to dark grey for Figures 5 and 9. Examples are given below (Figures 5g–i).



Line 80:
Consider replacing "continuous" with "multi-year year series".

I understand that continuous is confusing because the measurements were made only in summer. We will revise the text as suggested ("multi-year series GPS measurements").

Request for additional citation: I think some of the introductory discussion on subglacial hydrology is light on citations, particularly for more recent work. Should also include citations for discussion on tidal force balance at the calving front. (lines 35-42, and again supporting citations in lines 72-80). There are some important citations used later in the discussion of results on subglacial hydrology that could be incorporated again in the earlier introduction/background.

We will consider including additional references for Lines 35–42 (basal water pressure and tidal influence on ice dynamics) and Lines 70–79 (short-term speed variations in Greenland and Alaska). However, I would like to note that direct evidence of "basal sliding enhancement due to elevated subglacial pressure" is sparce.

Request for additional clarity: I found some of the detrending methods description confusing. For example, in some places the text uses "detrended" to refer to, what I believe, is simply the time series with the seasonal mean subtracted. In Figure 5, 2019 speeds certainly show a "trend" over the July period, though the mean is zero. However, I assume this detrending approach (where a seasonal acceleration or deceleration may be present) is a different approach used to the "stacking" described, where a mean diurnal speed is computed. Can you please provide more clarity on these methods?

“Detrended ice speed” was obtained by subtracting mean displacement from the positioning data. It is not a simple subtraction of the seasonal mean speed. The details are described in the Method section in Line 132–134. “To investigate the deviation of the ice motion from a general trend, the mean ice motion was subtracted from the positioning data. The mean ice motion was computed by linear regression of the positioning data obtained in each season. The residual speed and vertical displacement were used to discuss ice speed variations and surface uplift.” Actually, we do not use the word “detrended” in this method description, which I suppose is the reason for the misunderstanding. We will clarify the point by writing “The residual speed and vertical displacement (hereafter referred to as “detrended”) were used to discuss ice speed variations and surface uplift”.

Line 170 – how is significant acceleration defined here? Based on a threshold rate of change?

We write, for example, “the glacier significantly accelerated (Line 179)”, “significant year-to-year variations (Line 203)” and “semidiurnal variations are less significant (Line 229)” to refer to substantially large changes in ice speed. I understand that the word is used for “statistical significance”, but here we use it in place of “substantial”, “notable”, “considerable”. We believe this usage is usual and our texts are not confusing.