<u>Seasonal land ice-flow variability in the Antarctic Peninsula (tc-2022-55)</u>

Author Response to Reviewers (20/08/22)

Dear Dr. Berthier,

We thank both reviewers for their comments on our revised manuscript and were pleased to read that they find it to be "*very good"* (Reviewer 2) and that "*the quality of the manuscript strongly improved*" (Reviewer 1). We were particularly pleased to read that Reviewer 2, Dr. Ted Scambos, recommends the manuscript "*is ready to publish from a science standpoint*".

In the following response document, we provide point-by-point responses to the reviewers' final minor comments. As before, we have included the numbered reviewers' comments (*italicised in blue*), our responses (black text) and amendments to the original text (*italicised in grey*). Unless otherwise stated, line and figure numbers referred to below are in line with the revised manuscript with tracked changes submitted here.

Following your instructions, we have also checked carefully the manuscript for typos, missing co-authors and their affiliations, terminology, updates of data in tables, or updates of variables in equations and confirm that there are none throughout.

Kind regards,

Karla Boxall

(on behalf of the co-author team)

Reviewer #1

1. *The quality of the manuscript strongly improved and most issues were addressed adequately. In particular the discussion improved strongly and provides a very nice and interesting summary of the potential processes explaining the observed velocity patterns, highlights the needs for future research. Very good job!*

We thank the reviewer for their positive re-review, and were pleased to read they believe the manuscript has "strongly improved" and that the revised Discussion (Section 5) "provides a very nice and interesting summary of the potential processes explaining the observed velocity patterns".

2. *There are only very fee* [few] *issues open, which should be addressed before publication of the paper.*
3. *Most important is the poor data coverage for some flow lines and a clear description of the error computation.*

We thank the reviewer for raising these points. Please see our responses to the detailed comments below regarding the poor temporal data coverage for some flowlines, and the description of our standard error calculation.

Detailed comments:

4. *L280: Maybe you should note the poor data coverage at flow line 10. This might partly explain its pattern.*

We have now noted the poor temporal data coverage at flowline 10 as a potential reason for the observed non-summertime speedup signal. The revised text on Line 270 now reads:

"The latter likely arises from poor temporal data coverage, while the double peak associated with Flowline 8 is attributed to an anomalous wintertime speedup in 2016 which dominated the mean velocity signal of this glacier."

5. *Fig. 4 and 5: Moreover, it is still unclear, if you analyze only time periods with a "13-month Moving Mean" available in Fig. 4 to generate Fig. 5. In particular for flow line 16 the coverage by the "13-month Moving Mean" is quite small. Well, flow lines 5, 9, 15 and 17 have also quite limited temporal coverage. At least, you should mention this issue and its implications for Fig. 5.*

Thank you for this comment. We have reworded the text on Line 176 to clarify that only the portions of each velocity time series with 13 months of continuous data were detrended.

"Next, to accentuate intra-annual trends, we removed long-term trends in velocity over each 10 km^2 region (cf. Hogg et al., 2017; Gardner et al., 2018) using a 13-month moving average. At flowlines where the removal of a 13-month moving average was not possible, for example due to gaps in the time series, the data were excluded from our subsequent calculation of detrended monthly means."

6. *Moreover, it is still unclear how you computed the error bars. In line 127ff, you explain the calculation for the mosaics, but it is unclear how you obtained the error for the 10km^2 regions (mean of SE within the 10km^2 areas?) and for the detrended monthly ice flow (Fig.5, SE of all individual vel. Fields for a certain month?, how did you compute the error throughout the 10km^2 areas?). You talk about standard error in the figure caption and in the legend it is called mean standard error. Please clarify.*

We have added the word 'mean' to Line 173 to clarify that for each 10 km^2 region, we calculated a mean velocity and a mean standard error, for each month. The text now reads:

"To do this, we calculated mean velocity and mean standard error (cf. Sect. 3.2) at monthly intervals within a 10 km^2 region located directly upstream of the grounding line between 2014 and 2020."

Both the legend and the figure caption of Fig. 5 have been updated to read "mean monthly standard error" to clarify that the grey shading in Fig. 5 represents the mean standard error over each 10 km^2 region, averaged by month.

7. *L300 ff. This is an interesting hypothesis but quite speculative. What about flowline17-19 vs 6-9? You should rephrase it. e.g. remove "clear evidence" and state that more research is needed. I would suggest to analyze this hypothesis on yearly scales and based on long-term average.*

We thank the reviewer for their comments on this section, which was of course added at the request of Reviewer 2 (Dr. Ted Scambos). We appreciate that these signals are not universally observed across GVIIS' outlet glaciers and, in accordance with the reviewer's advice, have therefore slightly reworded the sentence as follows. Similarly, we have also added a new sentence on Line 296 to stipulate that more research and observations are ultimately required. Revised text reads:

"Within this trend, Figs. 4 and 5 also present evidence of the ability of select GVIIS' outlet glaciers to influence each other across the ice shelf, whereby the earlier acceleration of Alexander Island's glaciers initially arrest those flowing from Palmer Land, delaying the onset of their acceleration until the late summertime (compare, for example, the timing of peak velocity at the geographically opposite Flowlines 21 and 3, and Flowlines 20 and 4-5). Upon late-summertime acceleration, Palmer Land's glaciers then arrest the flow of those on Alexander Island in a similar manner. Continued monitoring of this phenomenon beyond the current Sentinel-1a/b observational record may shed additional light on the importance of this mechanism (or otherwise) for controlling the overall seasonal signals exhibited at these outlet glaciers."

8. *Section D1: I am still a bit confused by the plotted "fitted cosine wave". Flow line 6: Dominant frequency=3. As far as I understand your analysis a frequency of "1" stands for one full cycle per year. I would expect, that a frequency of 3 relates to "3" full cycles per year. However, the orange line for flow line 6 shows only one full cycle per year. Same for flow line 8. What is the unit of phase is it in "rad" or in "month"? What is the unit of the amplitude?*

For consistency in the interpretation of the amplitude and phase values, we chose to fit cosine waves with a constant frequency to all velocity time series. This constant frequency was ascertained from the most dominant frequency observed across all timeseries.

This is stated in the text in Appendix D:

"… a cosine wave, optimised to the most dominant frequency observed across all outlet glacier time series (1 month), is fitted to each time series"

It is also included in the caption of Fig. D1:

"Panels show mean monthly ice flow of each outlet glacier (blue; same as Fig. 5) with fitted cosine functions (orange) optimised to the most dominant frequency observed across all outlet glacier time series."

The unit of phase is radians, and the unit of amplitude is m d^{-1}. These units have been added to the headings in Table D1 and to the axis label in Figure D1.

Reviewer #2

1. *A few comments – The discussion in 5.1 is now very good, fundamentally what is needed are observations of melt days at a smaller spatial resolution than are currently widely available. Yes, the gradient of melt days with altitude is steep, but there are melt ponds at a few hundred meters' elevation in the AP, on the eastern side (where they are revealed more easily due to low snow accumulation). See attached photo.*

We thank the reviewer, Dr. Ted Scambos, for his re-review and were pleased to read he is contented with our revised Discussion (Section 5.1). We agree that currently there is not enough observationally constrained evidence at the required spatial resolution to implicate surface forcing as the primary mechanism driving the observed seasonality.

2. *No real changes to suggest to Section 5.1 except to remove the last sentence in the section: We would expect any subsurface meltwater to perpetually flow towards the grounding line due to gravity. It gives the wrong impression, that a firn aquifer on a slope would 'drain away' and not accumulate water. As Harper et al., 2012 and Koenig et al., 2013 note, there are perennial aquifers on the grounded and sloping Greenland ice sheet, and they pool water in the topographic lows and spill over, slowly and perennially, toward the coast.*

Thank you for this comment. We have removed the sentence from Line 384 as suggested.

3. *Ok, one more comment: the cooling trend is real (and likely tied to shifts in the PDO), but it's not like surface melting stopped anywhere where it was common before. And the cooling trend, following the PDO shift again, may be reversing. As you note, Banwell et al., 2021, showed near-record melting in 2020-2021 in the region.*

In response to this comment, we have reworded Line 376 to tone down the assertion that the cooling trend observed over the Antarctic Peninsula since the late 1990s by Turner et al. (2016) renders the existence of firn aquifers improbable. The sentence now reads:

"We note, however, that the formation and persistence of firn aquifers requires high levels of surface melt and accumulation (Harper et al., 2012; Koenig et al., 2012; Montgomery et al., 2020): phenomena which may not be prevalent inland of GVIIS during most of the Sentinel-1 era given the pervasive cooling of the Antarctic Peninsula over approximately the past two decades noted above (cf. Turner et al., 2016)."

4. *On Section 5.2, I note that while the opening paragraph makes a strong case for influx of CDW, and I'm sure that is happening, there is not a strong case for seasonality of the inflow. Ah, I see that is the first line of the next paragraph.*

We agree that Jenkins and Jacobs (2008) do not reference any seasonality with regards to CDW influx. We are glad to read that our first sentence in the second paragraph makes this point clear.

5. *In the first paragraph, for this last sentence: with inferred patterns of melting observed recently along the Coriolis- favoured flank of Dotson Ice Shelf, West Antarctica (Gourmelen et al., 2017). You might also cite the more wide-ranging work of Karen Alley (note, I'm a co-author on these papers, but they do cover many more of these features than the excellent Gourmelen work).*

We thank the reviewer for this helpful suggestion. We believe Karen et al. (2016) is particularly relevant here. This citation has been added to Line 399.

6. *Paragraph beginning 'Ultimately', I think you don't need the word 'historical' in that sentence.*

Thanks. We have removed the word 'historical' from Line 416.

7. *Reviewer #1 response, Comment #4: The near-grounding line focus of the speed-up, no matter the cause (ocean or surface melt) is more likely an indication that basal shear stress in the glaciers is large, preventing a rapid or extensive transfer of reduced longitudinal compression upstream. This is true for several coastal areas of Antarctica (e.g., Getz Ice Shelf, which –is seeing a strong ocean-derived basal melting, but little upstream propagation of increased flow speed).*

We thank the reviewer for sharing this insight. While no action is required for the current paper, this is a useful concept which we will keep in mind for our future research.

8. *I read through all the responses to the Reviewer 2 comments (mine) and I am fine with all of them.*
9. *My recommendation to the editor is that the paper is ready to publish from a science standpoint.*

Thank you. These statements are pleasing to read.

10. *A picture of Crane Glacier, looking downstream; the large blue area is an ice-capped meltwater lake. The image was taken in April 2013. The point being that extensive melting does occur upstream of the grounding line in the AP; for the glaciers feeding the GVIIS, a bit more spatial resolution in melt-day mapping is required (for another study at another time).*

We thank the reviewer for sharing this image. This will be of good use in our future, follow-up research.