Summary

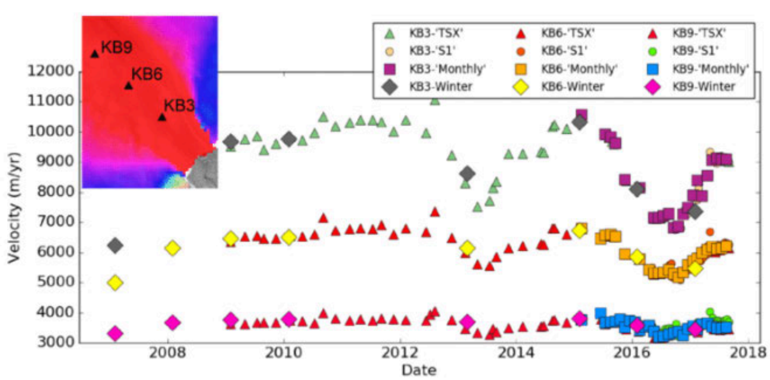
This study calculates Greenland Ice Sheet Discharge for the 20th century by extracting time series for all ice margin pixels that flow at speeds greater than 100 m/yr, comprising 263 discrete flux gates. The methodology is relatively straight forward and the manuscript well-written and easy to follow. The novelty of this work stems from an automated flux gate selection algorithm, which allows the authors to test discharge sensitivity to velocity thresholds and gate-to-terminus distance. The authors have made all data and related code openly-accessible and appear to have the framework in place to continually update the time series through the present. However, I suggest several methodological concerns be addressed prior to publication, primarily regarding the treatment of outliers, temporal averaging, and lack of detail describing the gate selection algorithm itself. Major points are listed first below, followed by minor points and technical comments.

Major comments:

<u>Treatment of outliers in velocity data</u>

On Page 10, line 5, the authors state that the signal to noise ratio may be reduced at the individual glacier level but that this noise is not apparent in the total ice sheet discharge time series. I disagree with this assertion and will highlight an example that I think demonstrates the need for a more careful treatment of outliers.

Distinct spikes are apparent in the Greenland total graph (Figure 6) from the ~monthly data in 2011 and 2013. These seem to be primarily the result of similar spikes in the SE sector (Figure 7). In the SE in 2011, there is a rapid fall of ~50 Gt (30%) and a subsequent rise again of ~40 Gt all within a ~3-month period, which is physically improbable. Looking more closely at the top 7 individual glacier plots in Figure 8, we see that the sector spike in 2011 is an artifact of discharge at Køge Bugt Glacier (located in the SE), which increases from a baseline of < 20 Gt/yr to over 40 Gt/yr in 1-2 months. Given the usage of annual surface elevations used in this study, this change must then be due to velocity, and would require an acceleration of over 100% in a very short time period. Below are velocity time series taken from Joughin et al. 2018 (https://doi.org/10.5194/tc-12-2211-2018), which shows no such dramatic acceleration during that time. From my quick glance at the individual glacier discharge data accompanying this manuscript, several other glaciers also occassionally exhibit large, abrupt changes that I suspect are untreated outliers.



Similarly, the next SE sector spike in 2013 is not present in either Køge Bugt or Kangerlussuaq Glacier, which are the largest two glaciers in this sector. This would mean that the remaining glaciers in the SE sector (which I estimate from the figure to roughly account for an average ~100 Gt/yr) would have to compensate for the ~50 Gt/yr increase. I'm skeptical of this because, to my knowledge, such an abrupt and short-lived acceleration in 2013 has not been previously documented.

These examples show that although signal noise at individual glaciers will typically be mitigated in the total ice sheet time series, large outliers at the more prominent glaciers will propagate to the sector-wide time series and also possibly to the total time series and impact annual averages. The outlier problem is amplified when linear temporal averaging is applied using noisy data points. I think the data quality could be improved by a simple low-pass filter, which would also make the individual glacier time series more robust for those who may use the data for local studies. It may be helpful to reference the velocity maps/mosaics associated with outlying points to assess if the pixels are particular noisy at that time.

<u>Temporal averaging</u>
How are annual averages computed from the nonuniform time series? I suspect that the series are resampled at uniform intervals prior to averaging, but this is not explicitly described in the manuscript. Even if resampled at equal intervals, the use of linear interpolation for missing time periods means that there is an inherent sampling bias that the authors should estimate, though it may be small. This could be done using the reference period with dense temporal coverage.

<u>Lack of text on automated flux gate selection algorithm</u>
I'd like to see more details on the algorithm included in the manuscript, especially since the automated algorithm is the key strength of this work. Some details are commented throughout the code samples, but it requires digging. I suggest a methods section describing the algorithm development that at minimum addresses:

1.) If and how frequent manual adjustments are needed due to continued retreat (terminus retreats behind 5km upstream of GIMP-determined terminus).
2.) The treatment of unconfined, radially-draining catchments – do they require additional corrections as shape and direction of dominant flow change?
3.) Brief description of treatment of floating ice shelves. By termini selection, do you mean grounding ice mask from BedMachine/GIMP or glacier front?
4.) Does the algorithm ever require "unfiltering" originally excluded pixels after gate migration? For example, though most glaciers accelerate toward the terminus, if a pixel 5 km upstream of a slow moving near-terminus pixel exceeds the 100 m/yr threshold, is it still excluded, or retroactively filled along the gate? I suspect this would only happen in some instances at radially-draining glaciers.

Minor comments

<u>Title and use of '2000-2018' period.</u>
The figures and the description that the period studied as '18 year' (abstract) indicate that the time series extends through the end of 2017 and excludes data from 2018. While the use of 2000 'to' 2018 could be taken to mean 'up until' 2018, '2000 to 2018' and '20XX to 2017' are interchangeably used throughout the manuscript and it is confusing to the reader which exact period is being referenced. For example, an average discharge from 2010 to 2017 is mentioned on line 6 of the abstract. Based on the usage of the title, is this taken to mean the average was

calculated over the period 2010 through 2016, excluding 2017? Similarly, on page 7, line 27, a sector average is described over the 2007 to 2017 period. If the terminology is consistent and this does indeed refer to 2007 *through* 2016, why is 2017 excluded in these instances? Otherwise, please consider either replacing '2000 to 2018' with '2000 through 2017', or editing the remaining 'to 2017' references for consistency.

<u>Page 2, Equation 1</u>
Perhaps specify that A is area (even though it's intuitive) so that all terms are defined.

<u>Page 2, Line 5</u>
"…and Q is the volumetric flow rate". This makes is sound like Q should be in Equation 1. Are you defining now for later use? If the term is not used again it might be best to omit.

<u>Page 3, Line 2</u>
Contribute should be "contribution"

<u>Page 5, Line 20</u>
The use of 917 kg/m3 density value should be noted again in the discussion when comparing to previous studies as it could be another, albeit small, source of difference.

<u>3.4.1 Missing Velocity</u>
Do the reported stamps refer to the time span midpoint, or the first date of the time span (first image)?

<u>Page 6, Line 23</u>
"This thickness adjustment adds 21 Gt to our baseline-period discharge estimate..."
Should be Gt/yr? Is this adjustment, described in Table A2 and as applied to the final estimates in Figure 6, added as a fixed value to the full time series or does the magnitude of the adjustment vary through time?

<u>3.4.3 Ice Discharge Uncertainty</u>
Is the temporal variability in coverage considered in error estimates? I would expect discharge estimates for a given time with, for example, only ~20% coverage to have a larger uncertainty than a time point with full coverage.

<u>4.2 Ice discharge (volumetric flow rate)</u>
<u>Page 7, line 26</u>
If 169 Gt/yr is 54% of total ice sheet discharge, this yields a total ice sheet discharge of ~313 Gt/yr. On line 28, 70 Gt/yr representing 32% of total ice sheet contribution would indicate that total ice sheet discharge is ~219 Gt/yr. These values are inconsistent with each other and with the preceding paragraph. Can some text be added here to clarify what these percentages represent?

<u>4.3 Volumetric flux</u>
I found this section confusing. By normalizing discharge by cross-sectional area, the authors are effectively describing interannual changes in velocity (since density is constant through time). I

think it would be easier to follow if described in velocity terms, but it may not be necessary to include this section at all.

Page 8, line 18
2013 maximum should be 2011 (as previously stated on page 7, line 24).

Page 9, line 29
"The King et al. (2018) 2005 peak discharge is 524 +/- 9 Gt dropping to 461 +/- 9 Gt in 2008 – a decrease of ~63 Gt. In our work, the 2005 peak is 515 +/- 50 Gt, dropping to 495 +/- 50 Gt in 2008 – a decrease of only ~20 Gt."

This comparison should be altered to either (1) compare annual averages between both studies, or (2) compare absolute max and min value between 2005 and 2008 from the ~monthly estimates (which look to be about 550 - 480=70 Gt from Fig. 6). The annual changes from King et al. 2018, plotted in red in Figure 1 from that paper, show an annual change of ~20 Gt, which is comparable with these results.

Figure 1
This is a very good figure.

Figure 2
The heatmap is an excellent addition to the manuscript and packs a lot of information into a very readable figure. Interesting to see sensitivity to cutoff velocities increases with upstream gate distance.

Figure 8 and discussion of 7 largest discharging glaciers
I accessed the individual glacier discharge data available on the data portal and calculated that 'IKERTIVAQ_M' glacier contributes a period average discharge of ~14 Gt/yr, which is larger than the average contribution from Nioghalvfjerdsbrae. Why was this glacier excluded from the top 7? If instead this is a reference to the top 7 glaciers spread throughout each sector rather than absolute largest 7, then consider adding a word on this for clarification.

Page 24, line 17
Is the gate number 263 or 264? Both values are used throughout the manuscript.

Table A2
Are these values given for the reference period (2015-2017)?